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[*Continued on page (III) of Cover.*

CONTINUOUS EXTRUSION OF LEAD CABLE-SHEATHS

By P. DUNSHEATH, O.B.E., M.A., D.Sc., Member.

(*Paper first received* 22*nd July*, 1936, *in amended form* 16*th October*, 1936, *and in final form* 3*rd March*, 1937; *read before* THE INSTITUTION 3*rd December*, *before the* TEES-SIDE SUB-CENTRE 17*th November*, *and before the* NORTH MIDLAND CENTRE 8*th December*, 1936; *also before the* SCOTTISH CENTRE 9*th March*, 1937.)

SUMMARY

The paper deals primarily with a new development in methods of producing lead cable-sheaths, in which the pressure required to extrude the lead is obtained by means of a motor-driven screw member instead of by the ram of a hydraulic press which has hitherto been universal practice.*

The author's experiments were commenced in 1929 when the first lead pipe was extruded by a continuous process, and the development has continued steadily up to the present day, and to the stage where commercial continuous lead-extrusion machines are now being delivered.

After reviewing in detail the disadvantages of former methods in order to explain the reasons for the development, the paper describes the construction and operation of the continuous lead-extrusion machine, and from considerations of the physical and metallurgical properties of the sheath demonstrates the improvements in the product achieved.

As the advantages attendant on the use of the continuous lead-extrusion machine are associated to some extent with the methods employed in melting the lead, and in the handling of the cable as it comes from the machine, special attention has been given to these features alongside the development of the machine itself. The paper describes improved lead handling and melting equipment and automatic reeling mechanism for the finished cable.

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(1) INTRODUCTION

It is estimated that the quantity of lead consumed per annum on the sheathing of electric cables in Great Britain alone is about 64 000 tons. Considering, then, the much larger quantity which must be used in the many cable factories throughout the world, it is clear that the improvement of the technique of lead cable-sheaths is one which vitally concerns both cable makers and cable users.

For many years past it has been known that various features of normal lead-sheathing practice have required attention, and much thought has been devoted to effecting improvements. In recent times the question is receiving wide attention because of costly failures which have resulted from sheath defects.

The intermittent process of sheathing a cable by means of a slowly reciprocating lead press—the only method employed from the early days of the industry—was known to be primarily responsible for most of the weaknesses which have caused trouble from time to time. It is not surprising, therefore, that more than one mind has been attracted during that period to the advantages of continuous extrusion.

(2) DISADVANTAGES OF HYDRAULIC PRESS EXTRUSION

Discontinuity and Economics

The features which differentiate fundamentally between non-continuous hydraulic press sheathing and the continuous method made possible by the lead extrusion machine, may be considered under two heads—economy of process and quality of product. In most works processes continuity of operation favours reduction in labour costs, not only because of the filling-in of otherwise unproductive intervals in the life of the plant, but also because continuous working makes possible automatic control of associated plant and processes. A hydraulic press must be stopped at the end of each extruded charge, the ram withdrawn, and a fresh charge run into the lead container, during which operation no cable is being sheathed. On the other hand, with a continuous lead-extrusion machine the cable may travel through the machine continuously, hour after hour, hot lead flowing in at one end of the machine as the completed lead sheath emerges on the cable at the other end.

Discontinuity and Die Conditions

Considerable as are the advantages of continuous extrusion from the economic standpoint, however, the effect on the quality of the product may be even greater. It is clear that continuous extrusion will encourage uniformity in the dimensions and properties. The conditions at the die—conditions which are all-important in controlling the characteristics of the finished cable sheath—may vary very appreciably with time in a non-continuous lead press and, therefore, with position along

* This paper describes the original continuous lead-extrusion machine as developed by Messrs. W. T. Henley's Telegraph Works Co., Ltd., and exploited by the Henley Extrusion Machine Co., Ltd. In fairness it should be stated that there is on the market another continuous lead-extrusion machine, constructed on somewhat different lines.

the length of finished cable. Unless the die temperature, the relative position of the components of the tube-forming members of the die, the pressure on the lead, the temperature of the lead arriving at the die, and other factors, all remain constant, it cannot be expected that the resulting tube will be uniform. From the very nature of the process the conditions of the lead flowing through the die of a hydraulic lead press must be different at the beginning of the cycle from what they are at the end. Reference to Figs. 1(*a*) and 1(*b*) will show that at the beginning of the charge the pressure from the ram is being exerted through the mass of lead along the paths AA′, whereas at the end of the stroke the pressure is being transmitted along the very much shorter paths BB′. If, as in some types of hydraulic press, the paths from the ram to different points in the circumference of the die differ in length or form, then another source of irregularity in operation is immediately introduced. This time the radial thickness of the pipe wall may vary around the circumference.

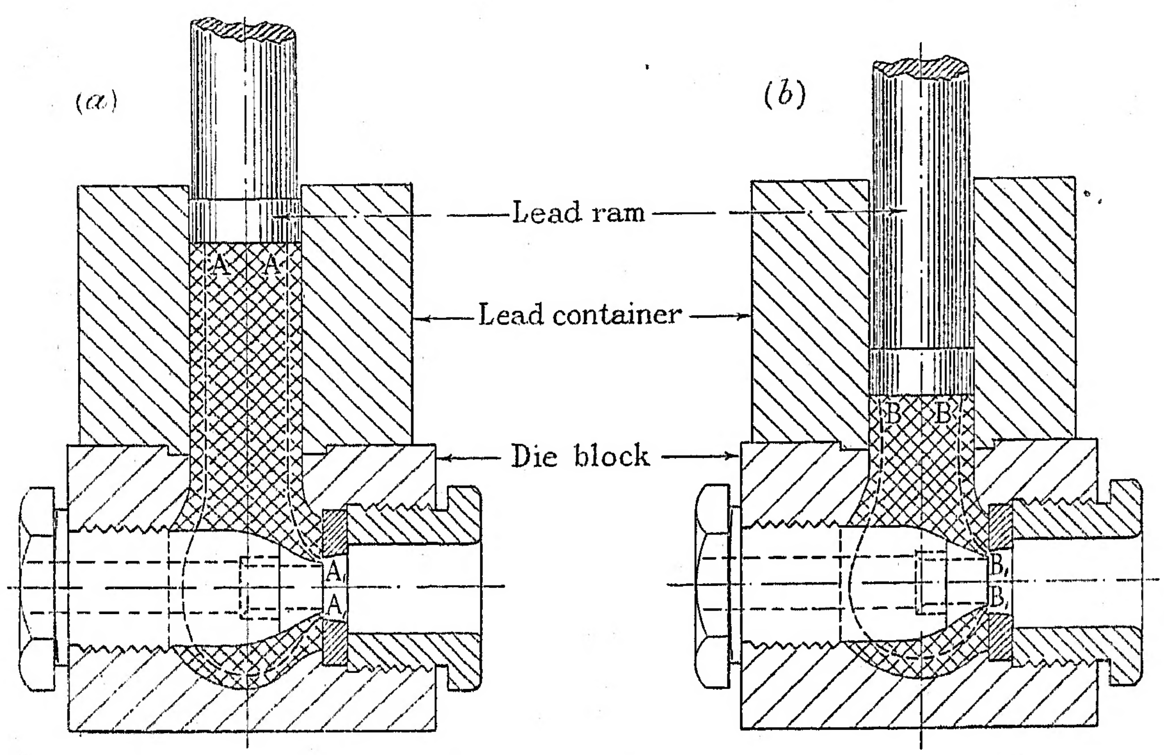


Fig. 1.—Diagram showing variation in effect of hydraulic press ram pressure on die conditions between beginning and end of stroke.

(*a*) Beginning of stroke. (*b*) End of stroke.

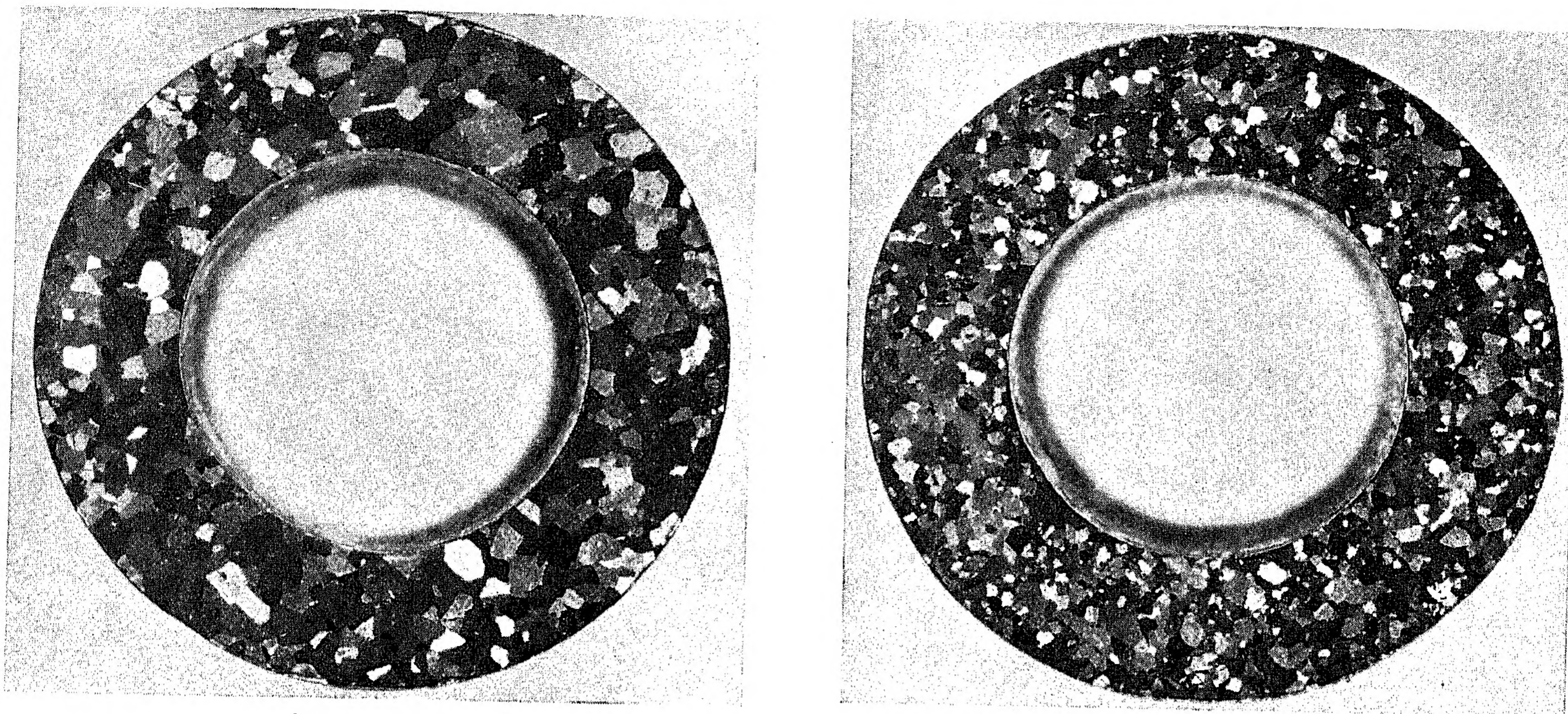
Still another factor, more prominent in some types of hydraulic press than in others, is the change of lead temperature at the die between the beginning and end of the ram stroke. As a result of these two phenomena it is not an uncommon experience to find a steady longitudinal variation of thickness in the wall of a pipe throughout a single charge.

It follows from the consideration of the causes of variation just discussed that in order to comply with a given minimum thickness of lead wall a larger total quantity of lead is required than if there were no such variation. If continuous extrusion, then, will avoid these characteristics of the hydraulic press and give more uniform lead, not only does there result an advantage to the user in gaining a more uniform product, but there is also a considerable economic advantage for the manufacturer in the saving of lead required.

Oxide Inclusions and Welds

A defect encountered with cable sheath made on hydraulic presses, which is even more serious than any of those already mentioned, is the inclusion in the finished pipe of welds between separate faces of metal which at some stage have been exposed to the air and have become slightly oxidized. Provided sufficient time is allowed to elapse and sufficient pressure applied at a sufficiently high temperature, two separate masses of lead will weld together completely as one homogeneous mass if the faces are kept clean and free from oxide. In such cases the fundamental crystals will grow right across the line of previous cleavage and so completely heal the breach that neither microscopic nor mechanical tests can reveal any weakness. As an example of this phenomenon Fig. 2 (see Plate 1) shows sections of a pipe which has been cut completely into four sections with four knives at right angles only a few inches from the point where the pipe was actually formed at the die. It will be seen that the crystal structure is perfect and the section is completely free from any sign of welds or of any indication that the lead had been parted. When a layer of oxide is formed, however, the story is quite a different one and an incipient weakness is at once introduced. Fig. 3 (see Plate 2) shows typical examples of the weakness introduced by defective welding through oxide inclusions. Unless special precautions are taken all hydraulic lead presses are liable to produce this defect. Fig. 4 shows further how there is a tendency for oxide layers to be segregated into a local line of weakness. In a mass of lead, moving under pressure from behind, a warmer and therefore softer centre core tends to "spearhead" into the mass. An originally flat transverse face folds backward at the sides as the stream of lead moves forward, and, where a series of faces each containing oxide or other impurity follow after one another due to successive charges, the impurity is smeared on to any obstructing surface and

Plate 1



Unquenched. Quenched.

Fig. 2.—Sections of pipe which was cut completely into 4 parts just before passing through the die. Owing to absence of oxide, the cuts have healed completely and left no weakness.

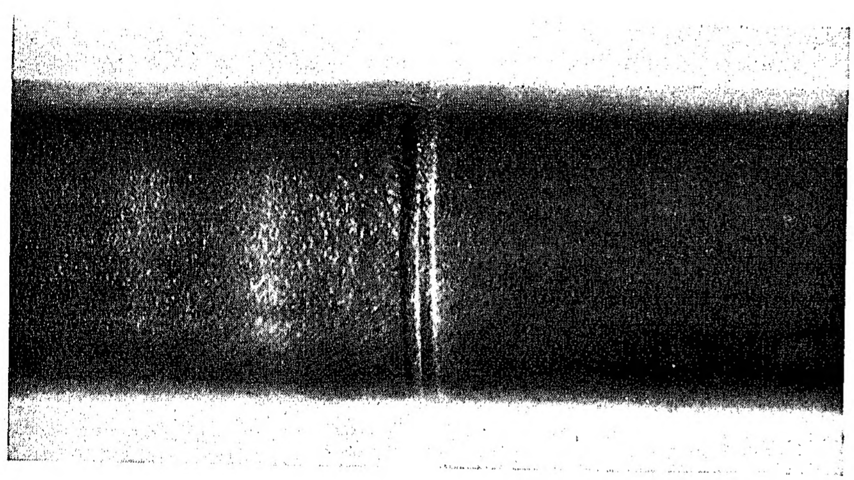


Fig. 5.—A bad stop mark such as may be produced by a hydraulic press.

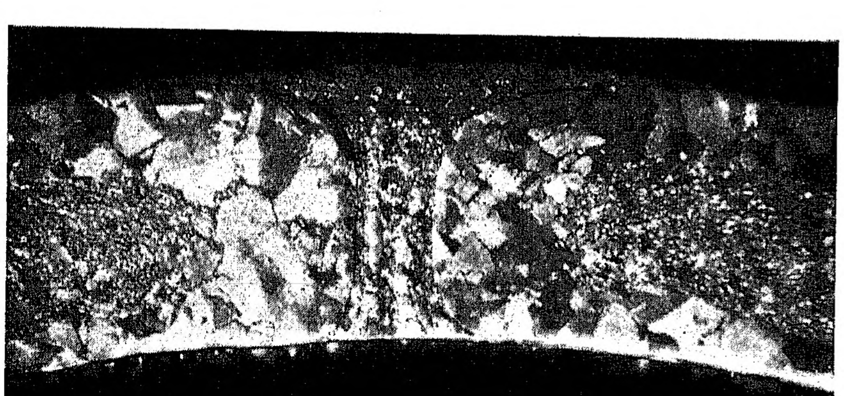


Fig. B.—Well-known incipient fissure due to oxide layering. Crystal systems distinct on two sides.

[*Figs.* B *and* C *are referred to in the author's reply to the discussion on page* 375.]

Fig. C.—Line in structure brought out by deep etching where metal has flowed over a dividing member and joined up again. One homogeneous crystal system.

(*Facing page* 354)

Plate 2

Fig. 3(*a*).—Circumferential oxide inclusions segregated in pipe wall when made by a hydraulic press.

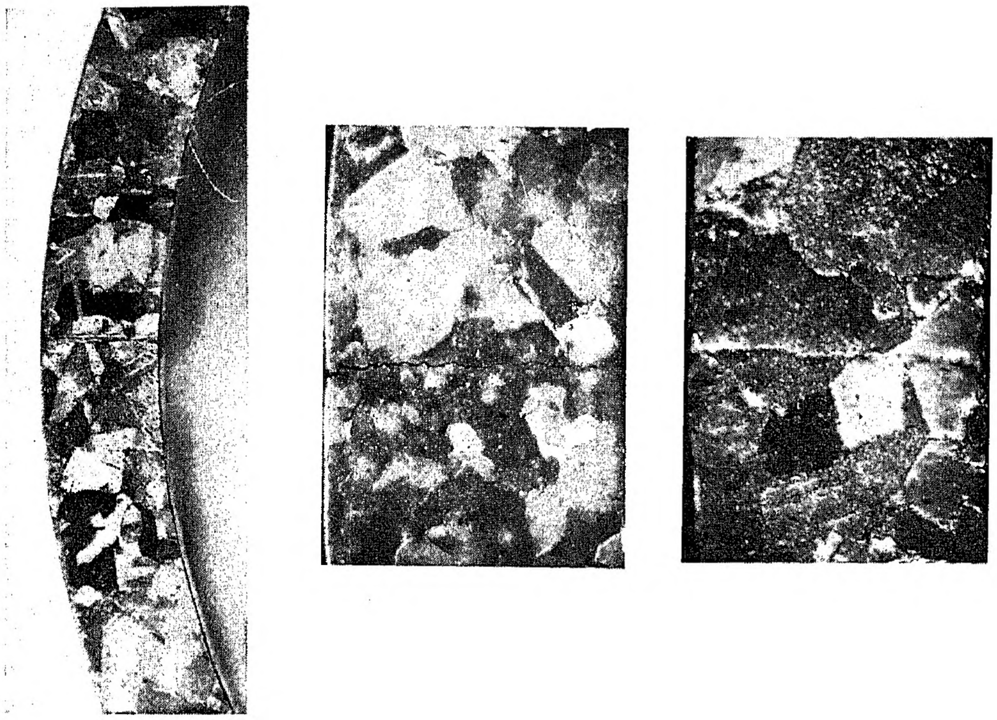


Fig. 3(*b*).—Radial oxide inclusions segregated in pipe wall when made by a hydraulic press.

Fig. 3(*c*).—Tongue-form inclusions segregated in pipe wall when made by a hydraulic press.

remains collected beyond the obstruction, as shown. Such segregation of non-lead material may result in actual split lead or exist as an incipient split only to open up subsequent to installation of the cable when heating, vibration, or other deteriorating influences, occur.

Stop Marks

When sheathing long lengths of cable, or even with short lengths when the sheath has a large cross-section, it is usually necessary to stop the lead press and recharge the container with lead once or more in the single length. It is clear that that part of the cable sheath remaining

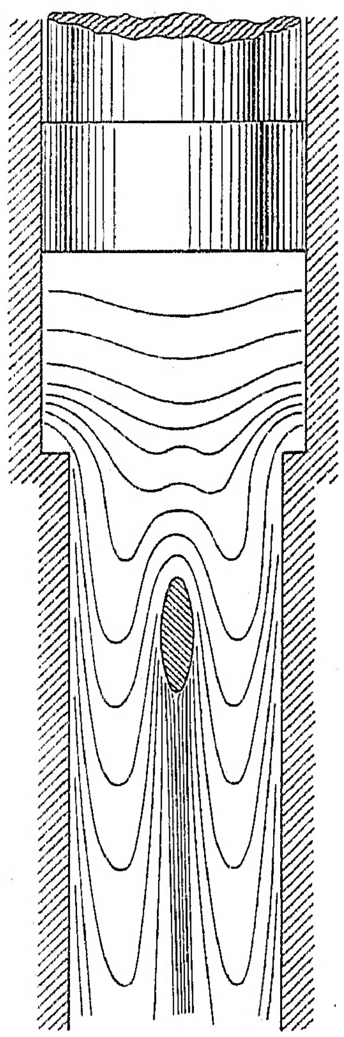


Fig. 4.—Diagram illustrating segregation of oxide layers when passing a barrier in the line of flow.

in the die during this process, which occupies several minutes, may be a further source of weakness. If the relief of pressure on the ram and lead causes a relative movement between the pipe already formed and the mass of lead in the forming chamber waiting to be extruded, care is necessary to ensure that the sheathing is not stretched at this point. The extent of this effect on the sheath varies with different presses, and to some extent is under the control of the operator; it can, however, almost always be traced as the "stop mark" on the surface of the finished cable sheath, an example of which is shown in Fig. 5 (see Plate 1).

Quite apart from the effect on the sheath, the stoppage of the cable in a lead press for recharging may introduce a weakness in the cable itself. The prolonged application of heat to a local spot during the time required to withdraw the ram, run in the fresh charge, and allow to solidify, is, of course, more dangerous than the heating applied during the steady running of the press.

One further disadvantage of the lead press stop in the case of alloy sheaths is the effect on the constitution of the metal at the point where the pipe is connected to the mass of metal in the forming chamber. Prolonged heating in this way may cause separation of one component of the alloy, introducing a metallurgical defect which would be particularly dangerous in the case of a submarine cable, or cable for other positions where the fatigue limit is of importance.

(3) IMPROVEMENTS IN HYDRAULIC PRESS PRACTICE

The files of the Patent Office show that scores of patents have been filed during the past twenty or thirty years for different forms of die chamber to facilitate the production of uniform and flawless lead cable-sheath. More recently the activities of inventors have been turned into two other directions for improving the performance of the hydraulic cable sheathing press, firstly by the removal of the oxidized surface from the existing charge before the following charge is admitted, and secondly by the prevention of the oxidation. The removal of the oxide is effected by the mechanical removal of the surface or by melting, while the prevention of the oxide layer is effected in various ways. In some of the methods the space above the existing charge is never uncovered, but as the ram is withdrawn a vacuum is formed until the new charge of molten lead is admitted. In other systems the passages and lead container are charged with a non-oxidizing or actually reducing gas which also surrounds the stream of lead from the melting-pot.

The most striking development in hydraulic cable sheathing presses during the past decade has, of course, been the appearance of the Judge "straight-through" press, which has already been fully described elsewhere.* No further remark is needed here than to recall that with this form of press all ports, die boxes, etc., are obviated. The molten lead is cast as a large slug around the cable, and after cooling is then reduced in dimensions by the advancing ram to form the cable sheath, remaining throughout the operation a complete hollow cylinder. It follows that with this type of press many of the disadvantages of other hydraulic presses are overcome. The surface of the lead exposed to the air on the withdrawal of the ram is an annulus and consequently, as it folds forward under pressure from succeeding charges, it assumes the form of a long cylindrical wedge or longitudinal scarfe. It was shown earlier, in connection with Fig. 4, that where "spearheading" of a folded oxidized surface recurred during the extrusion process, the repetition of the process, charge after charge, resulted in parallel surfaces of impure lead coming together and forming thin "sandwiches" which constituted weak places in the finished tube. Where the segregation is controlled by smearing the lead stream over an internal barrier such as a bridge in a die box, mandrel, or point-holder, then the sandwiches are laid up radially and may produce a weakness in the tube in the form of a radial incipient seam. In the case of the "straight-through"

* See, for example, *Journal I.E.E.*, 1928, vol. 66, p. 280, and *Engineering*, 1931, vol. 131, p. 567.

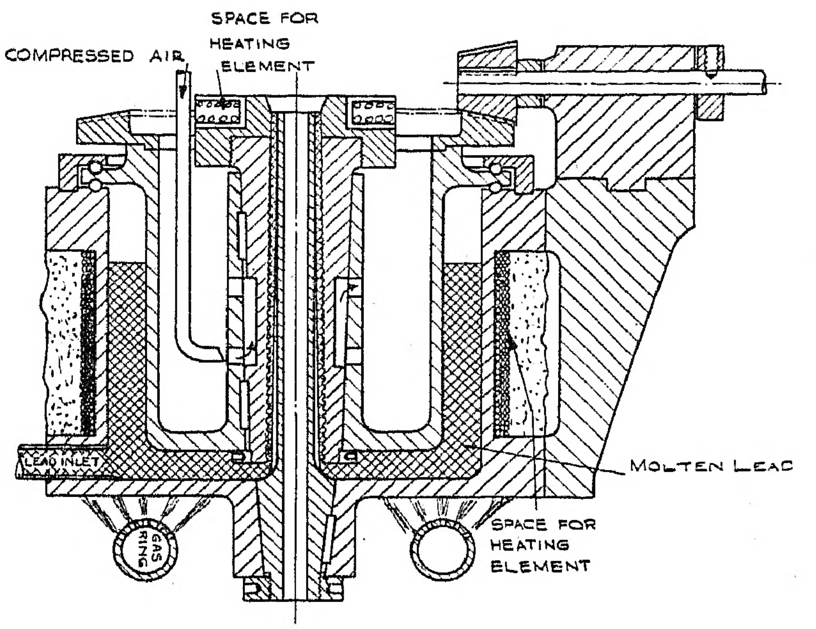


Fig. 6.—One of the earliest continuous lead-extrusion machines which worked in 1929–30. On this machine lead pipe was first produced continuously in December, 1929.

press, however, it will be clear that the sandwich segregation is in the form of concentric sandwiches passing harmlessly radially inwards and outwards to the inner and outer surfaces of the sheath. Notwithstanding these advantages over other types of hydraulic press, however, the straight-through press shares with them all the disadvantage of discontinuity.

(4) THE CONTINUOUS LEAD EXTRUSION MACHINE

Previous Attempts

For many years past attempts have been made to extrude lead cable-sheaths continuously instead of by the usual hydraulic press. Over thirty years ago the use of a screw impeller type of machine was suggested, but no success seems to have followed the proposal. Quite a number of arrangements have been put forward in which molten lead is pumped by a series of reciprocating pumps into a common container where it is cooled and passed to the forming die. Cogwheel pumps have also been tried as a casting machine with some success, and a system in which a reciprocating plunger provides a semi-

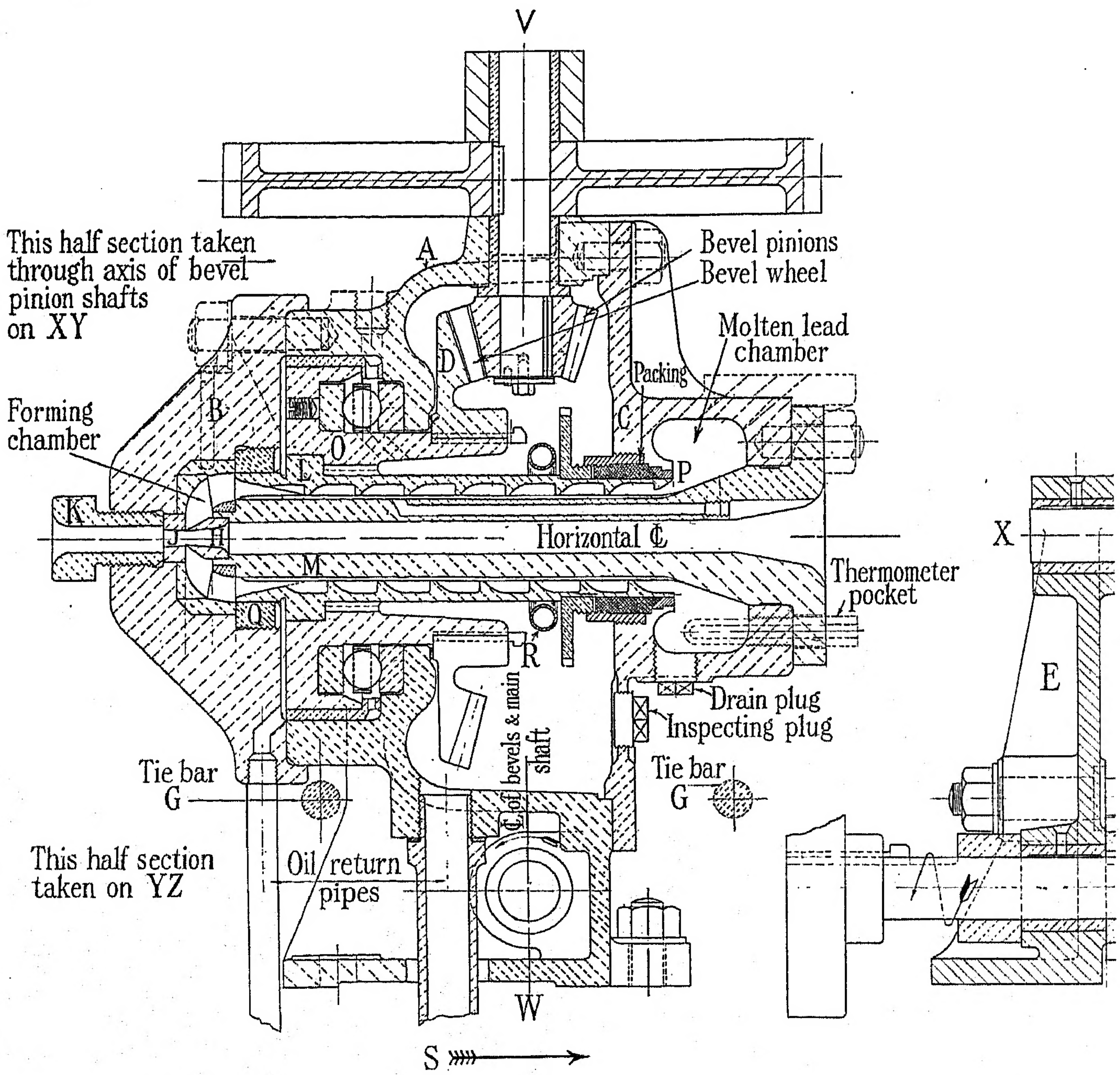


Fig. 7.—Arrangement of Henley lead-extrusion machine (development stage).

continuous extrusion through the annular space between the plunger and a surrounding die has also produced pipe. In the most successful of these experiments, however, it cannot be claimed that true continuous extrusion of lead cable-sheaths was effected.

Author's Early Experiments

The author's early experiments, carried out in 1929 and 1930, employed a series of vertical-axis machines. An open-topped cast-iron cylindrical pot was fitted with a ball race on its upper rim and had fitted, centrally to its base, a hollow tubular point-holder fluted longitudinally on its outer surface. Surrounding the point-holder was the impelling member, consisting of a deeply dished cover for the pot, the inner surface of the depression having a coarse screw thread. This cover carried by the ball race on the rim of the pot had fixed to its upper face a bevel wheel which engaged with a driving pinion for rotating it about a vertical axis. In the concentric groove was fitted an air cooler operating on the screwed portion surrounding the splined point-holder. The outer case contained the molten lead which flowed up into the space between the vertical fixed point-holder and the surrounding impeller.

The general construction of these original models is shown in the section of Fig. 6, and in December, 1929, a lead pipe was first successfully extruded with the device, employing a $\frac{3}{4}$-h.p. motor. The pipe had many defects, and various modifications were made in the construction over the next six months. In July, 1930, a 12-ft. length of really passable pipe was made, and again for another six months improvements resulted from failures and redesign of components.

Early in 1931 it was decided to construct a still larger model and to turn the axis of the machine into a horizontal direction in order to facilitate the handling of the cable. As the principle of this early machine has been followed in the later development, and as this actual machine covered many hundreds of miles of cable before being finally abandoned, the main features will be described by reference to Fig. 7.

The left-hand drawing shows, below the axis, a vertical

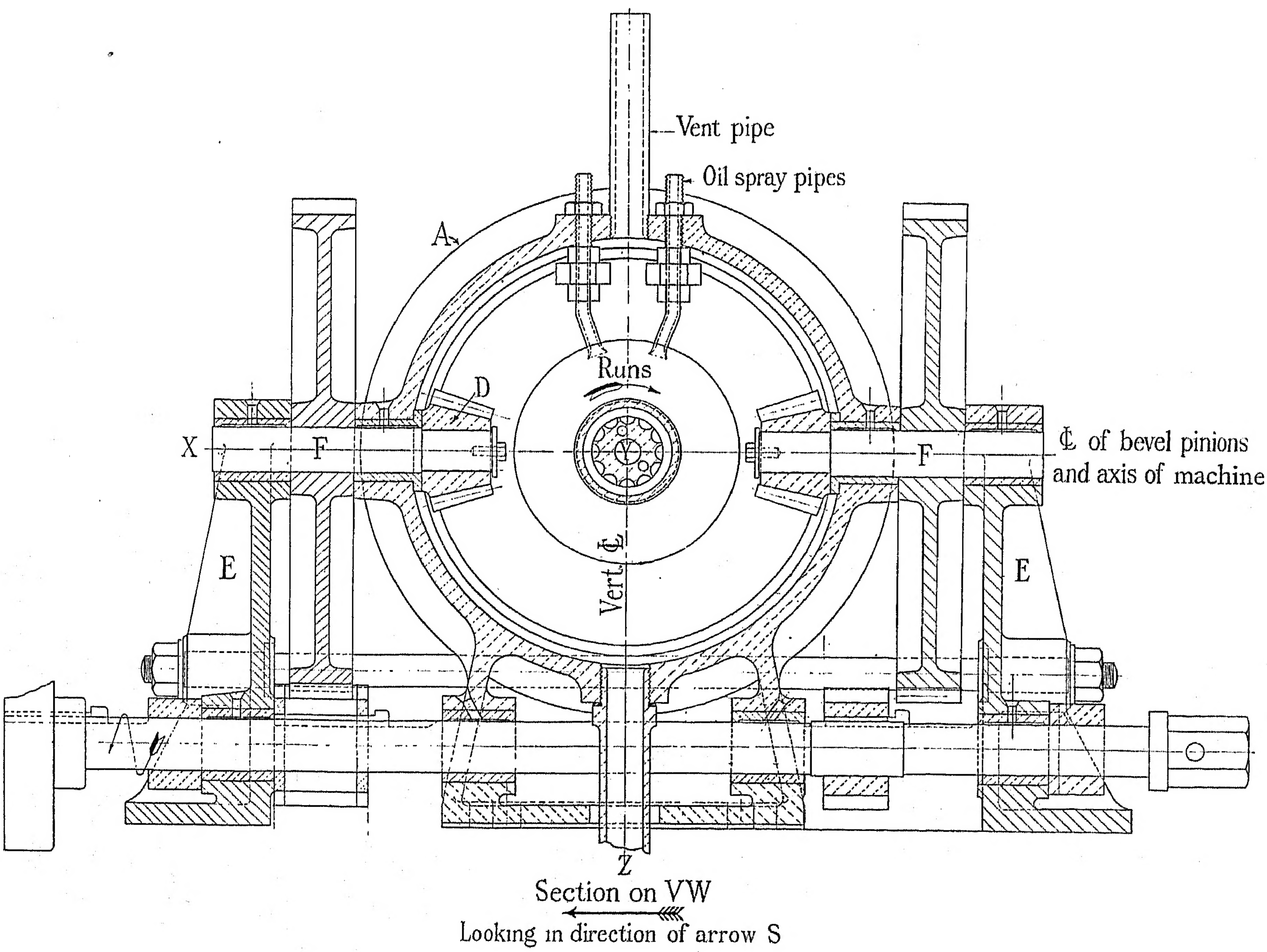


Fig. 7 (cont.).

longitudinal section, and, above the axis, a horizontal section, while the right-hand view shows the driving arrangements in a vertical transverse section.

The main frame casting A of the machine carries a front cover B and back cover C. The front cover B forms the die chamber with die J and adjusting nut K, which surrounds the emerging pipe as it is extruded. Supported from the back cover C is the point-holder M carrying the " point " H which controls the inner diameter of the pipe formed between point H and die J. In this model the outer surface of the point-holder was fluted or splined longitudinally as indicated in the sectional view on the right. Surrounding the splined point-holder and separated from it by a small clearance is the driver L, which is a tubular nut supported by the ball-race housing O. Keyed to this same member is the bevel wheel D, which engages with two bevel pinions on transverse shafts FF shown in the right-hand view.

At the rear (right-hand) end of the machine there is a space surrounding the root of the point-holder which communicates with the space between this member and the surrounding driver. This is the molten-lead chamber into which lead is fed from the melting pot; to prevent the escape of this lead around the end of the rotating driver a gland P is provided. At the front end of the driver another gland Q is also arranged to prevent the escape of lead from the forming chamber immediately behind the die.

In the operation of the machine molten lead flows into the annular space bounded by the splined surface of the point-holder and the screwed surface of the driver, and is immediately solidified by the cooling spray from an embracing perforated cooler ring R. Through the reduction gearing (shown in the right-hand view) and the two bevel pinions, the power from an electric motor is transmitted to the bevel wheel, and the driver nut is rotated in such a direction that its internal thread, engaging with the solidified lead, carries the metal forward. The continuous screw thread builds up sufficient pressure in the forming chamber to extrude the lead between the point and die, and pipe or cable sheath as required is formed.

This machine was put into operation in 1931 on the sheathing of small cables of various kinds, the manufacture of lead wire strip, etc., and ran successfully until taken out of commission about a year ago. It was found that the machine, although completely successful for the purpose for which it was designed, required excessive maintenance, and in 1933 a larger and more robust design was prepared for adoption as a commercial standard. The experience obtained in the running of the small machine for four years, and a more robust model for well over a year, during which time many hundreds of miles of commercial cable had been sheathed, demonstrated the important requirements necessary in a continuous lead-extrusion machine, and these have been taken care of in the design of subsequent commercial machines.

One of the principal features which have demanded attention has been the selection of special steels to withstand the unusual conditions where wide ranges of temperature exist in one and the same member. The extended runs over several years have been necessary to eliminate heat distortion which may have deleterious effects, for instance the displacement of the die relative to the point, so interfering with the accuracy of the extruded sheath. The design of the mechanical drive has also called for great care with a view to combining high efficiency and absence of wear with simplicity of construction.

Modern Construction

Fig. 8 shows the ultimate design adopted in which the machine consists of two units. The upper part contains the main cast-steel casing carrying back and front covers, lead-impelling portions with molten-lead chamber, point holder, driver with thrust bearing, and die-adjusting mechanism; and the lower part, a cast tank base which, in addition to housing part of the reduction gear, accommodates the oil used for flooding the thrust bearing and gear wheels.

From the left-hand sectional view it will be seen that several major improvements have been made on the design of the early machine. As will be seen from the right-hand view, a balanced drive on to the main impelling member has been achieved by a double train of spur wheels one on each side from the bottom shaft which is common to both. By a device well known to gear specialists and frequently employed, the torque is divided equally between the two trains. By leaving adequate clearance in the bearing P, the bottom shaft floats and the driving torque distributes itself equally between the two side wheels Q and R. The result is that the upwards and downwards thrusts on the final wheels are balanced, so reducing the tendency to eccentric wear of bearings to a minimum and at the same time reducing the tooth load to a half of what it would otherwise be. Complete accessibility to the gearing is provided by the inspection doors X and Y, and the lower main train of wheels is quickly demountable by the drawing forward of the cast stool Z.

As some of the most important features in the finished cable sheath depend on the mechanical construction of the forming chamber, considerable thought has been given to the design of this part. The essential requirements are a rigid support of the " point " relative to the die to facilitate uniformity of sheath wall thickness and the correct stream-lining of all boundaries of the chamber to prevent undue layering of the metal on its way through to the die. Many different configurations of the forming chamber have been experimented with, and the one shown combines the required relative rigidity of point and die with circumferential uniformity to prevent the occurrence of spearheading and formation of folds as discussed in connection with lead press operation. After the lead has left the impelling threads it is distributed circumferentially by various spillways in the forming chamber which produce a completely homogeneous stream of metal. There are many minor though important features of construction which do not show in the drawing, but one which perhaps should be mentioned is the employment in the up-to-date machines of threads on both members, and the longitudinal variation in the depth of the thread. Although the oxide layers met with in lead press practice are, of course, absent in a lead-drowned continuous extrusion machine, it has been considered

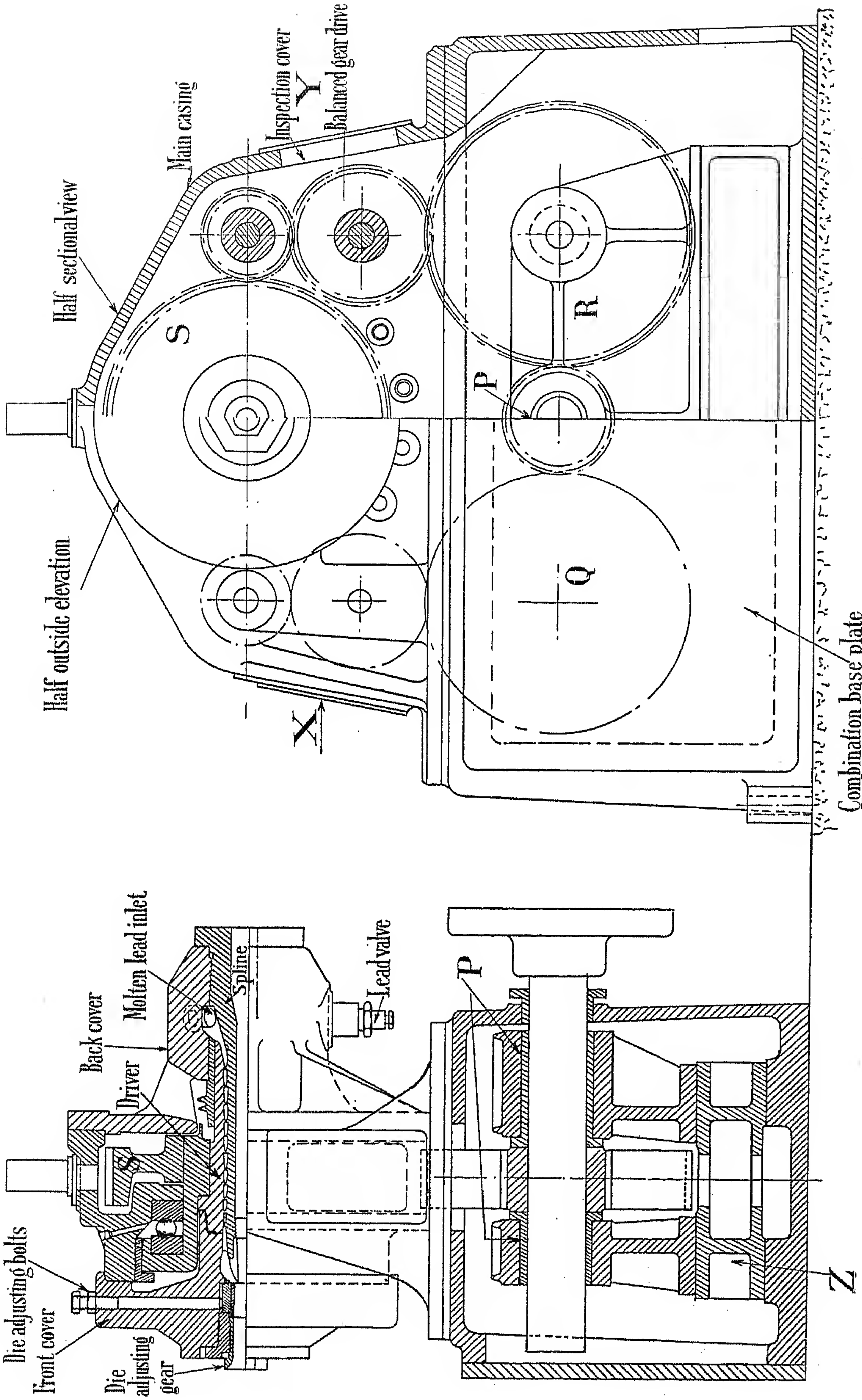


Fig. 8.—Arrangement of Henley extrusion machine.

advisable to avoid in every possible way the formation of " layering " of the lead, and this special formation of the impelling members contributes very materially to such a result. Mention should also be made of the means adopted for preventing escape of the high-pressure lead through the clearance space between the fixed and rotating members constituting the forming chamber. The very simple device of providing threaded surfaces has met the difficulty. Any lead entering the space is immediately engaged by the threads which provide the necessary back-pressure to prevent further escape.

As will be appreciated, lubrication arrangements in a machine of this kind are all-important, and a very efficient system has been worked out. An oil pump draws oil from the base tank, passes it through a cooler and distributes it via tell-tale indicators and separate pipe circuits to the thrust bearing, the radial housing bearing, and the wheel train, from all of which it falls again to the base tank. The thrust bearing, although continuously flooded with oil from a separate supply, is provided with additional safeguards in the form of temperature indicator and warning in the housing, and a visual flow indicator in the oil-circulation system.

A wide range of conditions has to be covered, from starting with the machine frozen up with solid lead requiring a heavy torque, to running after warming up, which calls for more or less torque depending on whether the machine is extruding large, thick cable sheaths requiring volume of lead without much pressure, or small, thin sheaths requiring pressure and little volume. The arrangements must also be sufficiently flexible to cover soft lead and hard alloys.

A range of machine sizes extruding up to 5 in. diameter cable core has been standardized, and the motor for the Type 1 (cable core 1 in. diameter) is a drip-proof separately-excited interpole motor with stabilizing turns. The motor is designed to withstand heavy momentary overloads and is capable of exerting the required starting torque and of running at low crawling speeds, also under severe overload conditions, whilst the solid lead is thawing out.

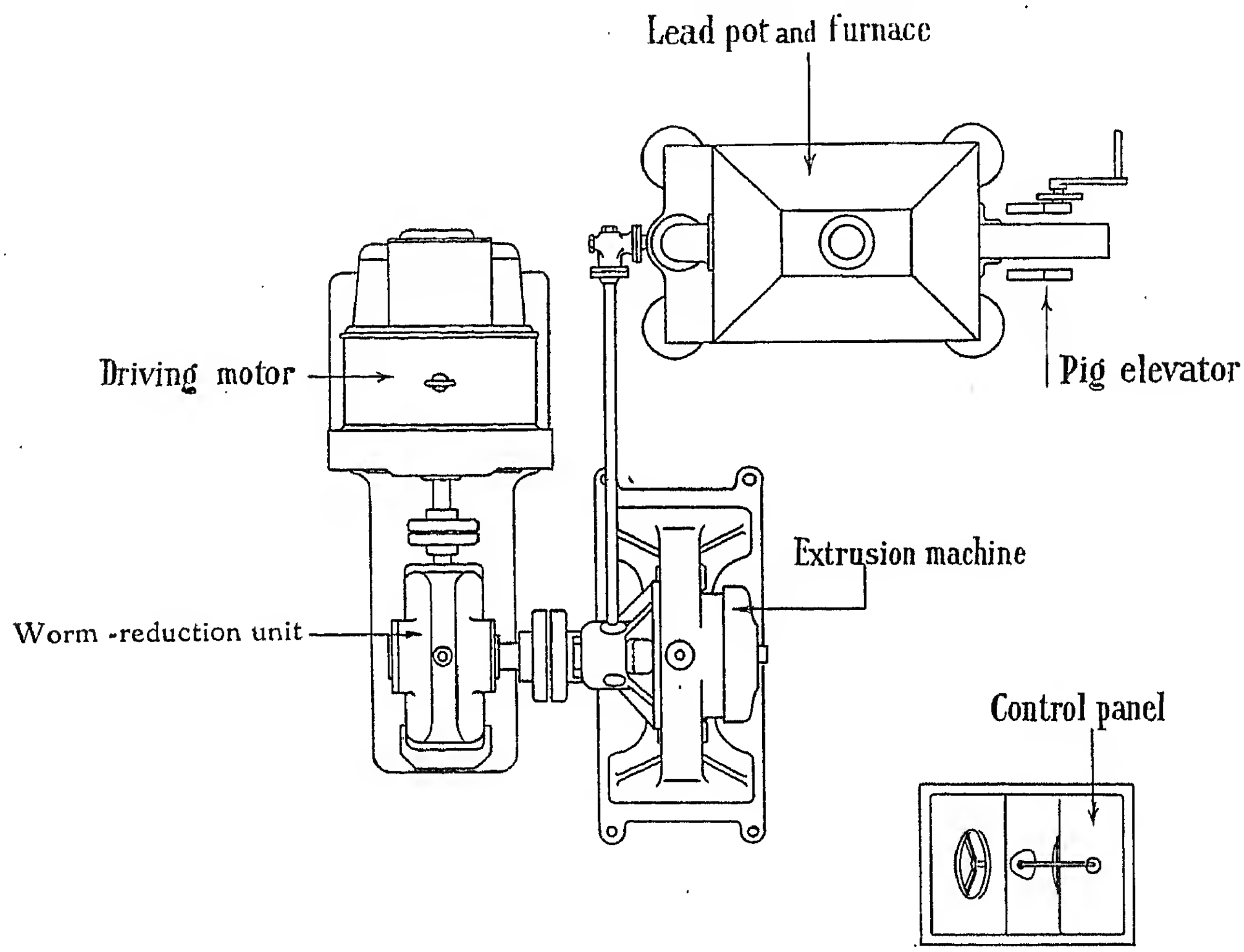


Fig. 9.—General layout of Henley lead-extrusion machine, showing electric drive.

Electric Drive

The electric drive of the continuous lead-extrusion machine has called for very careful thought and collaboration between the machine constructors and the manufacturers of motor and control gear. The motor stands to the side of the extrusion machine as shown in the plan view, Fig. 9, and the drive is transmitted through a standard worm-reduction gear.

Economical operation of this motor over the wide speed range required (30 to 1 350 r.p.m.) is achieved by a combination of Ward–Leonard and shunt control. An additional advantage is that the speed remains practically constant at any given setting of the control regulator, irrespective of variations in load applied to the motor, a very desirable feature in the operation of the extrusion machine. Heavy torques are also obtainable while the motor is under Ward–Leonard control, without corresponding heavy current-peaks being taken from the supply mains.

The motor-generator which supplies current to the main driving motor can comprise either a d.c. or an a.c. driving motor. If the supply is alternating current an

exciter is included which supplies the excitation current both for the generator and the main motor driving the extrusion machine.

The machines comprising the motor-generator set with or without exciter are coupled together and mounted on a cast-iron bedplate, and this part of the equipment can, of course, be mounted in any convenient position and need not be in the immediate vicinity of the extrusion machine.

The switchgear controlling the equipment comprises the following:—

(1) *A starter for the driving motor of the motor-generator set.* This calls for no comment, being of standard type.

(2) *Contactor panel.* This consists of a floor-mounting sheet-steel cubicle containing the contactors for making and breaking the circuit between the generator and the main motor driving the extrusion machine, together with overload relays and an ammeter shunt in the generator—main motor circuit.

(3) *A main control pillar.* This, as its name implies, forms the main control for the operation of the extrusion machine, embodying both the electrical controls for the operation of the electric drive and the various cooling and lubricating controls and temperature indicators requisite for successful operation.

The electrical controls embody the following:—

A. A red indicating light to give warning when the motor-generator set is running and the main motor field excited.

B. "Start" and "stop" push-buttons for closing and opening the contactors in the contactor panel mentioned above.

C. A handwheel-operated regulator combining both a potentiometer regulator for controlling the shunt field of the generator when the main motor is under Ward–Leonard control at the lower half of the speed range, and the shunt regulator for controlling the main motor field when working at the higher end of the speed range, the whole range of speed being controlled by the one handwheel.

D. An ammeter in circuit between the generator and main motor armatures operated from the shunt mounted in the contactor panel. This instrument can be calibrated to indicate torque developed by the main motor.

In addition to this electrical equipment there are, mounted on the control pillar, temperature indicators, oil-flow control cocks, and indicators, an oil-pressure gauge, cooling-water valves, and a temperature warning indicator.

The complete control panel is compact in form and intended for mounting in a convenient position alongside the extrusion machine.

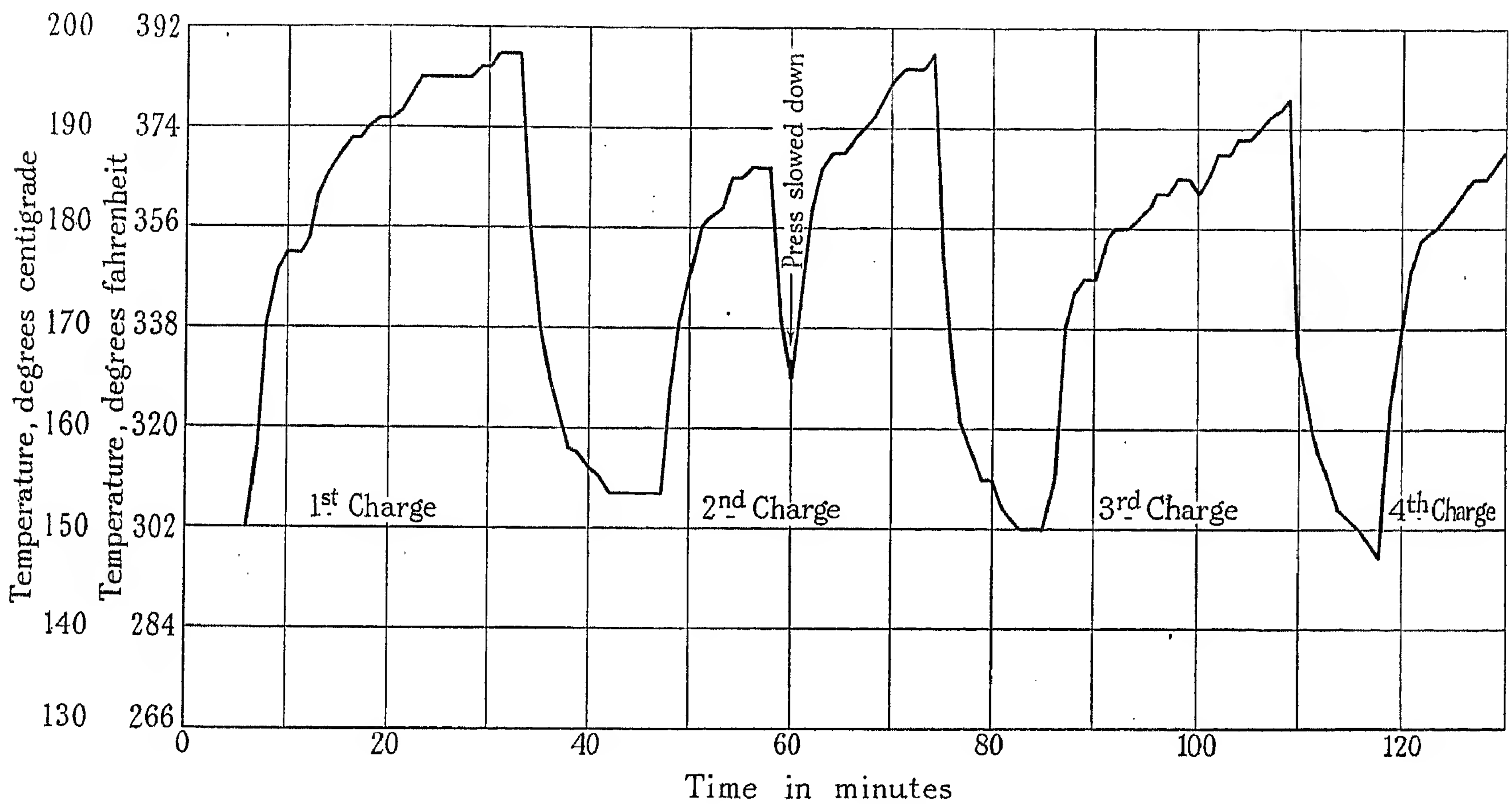


Fig. 10.—Variation of die temperatures recorded in a hydraulic press through consecutive charges.

Performance

It will be appreciated that the output of cable sheath from a lead-extrusion machine depends on the particular size of machine, the size of pipe being extruded, and the metal employed—whether lead or alloy. The weight per hour varies from about 2 000 lb. for the smallest machine, equivalent to about 450 yards of cable with 1 in. diameter core, to 4 000 lb. (or 200 yards) for a 3-in. machine sheathing 3-in. cable. In the case of hard alloys, 0·85 % antimony, for instance, the output is reduced by about 20 %. The power required on the Type 1 machine

seems to be well under the 35 h.p. provided, the majority of sheaths taking only about 20 h.p.

An interesting feature in the comparison with hydraulic lead presses is to be found in the variation of die temperature with time. Fig. 10 shows this variation in a series of tests on a hydraulic lead press. Thermo-couples were inserted in holes in the die, and the curves show what a wide variation of temperature occurs during the extrusion cycle. A similar series of determinations carried out on the continuous lead-extrusion machine shows practically no variation whatever, the temperature remaining uniform within a few degrees over long periods of time (see Fig. 11).

Uniformity in dimensions is, of course, a very important quality of the cable sheath, and involves two different factors, variation around the circumference and variation along the length. British Standard Specifications call for a minimum value of the mean thickness around the circumference at any point in the length, and permit a 10 % departure at the thinnest part. With normal hydraulic press extrusion such tolerance is often required, and to ensure compliance considerably more lead must be used than is theoretically necessary. The experience that has been gained indicates that a cable sheath extruded continuously has negligible variation on dimensions longitudinally, while a tolerance of

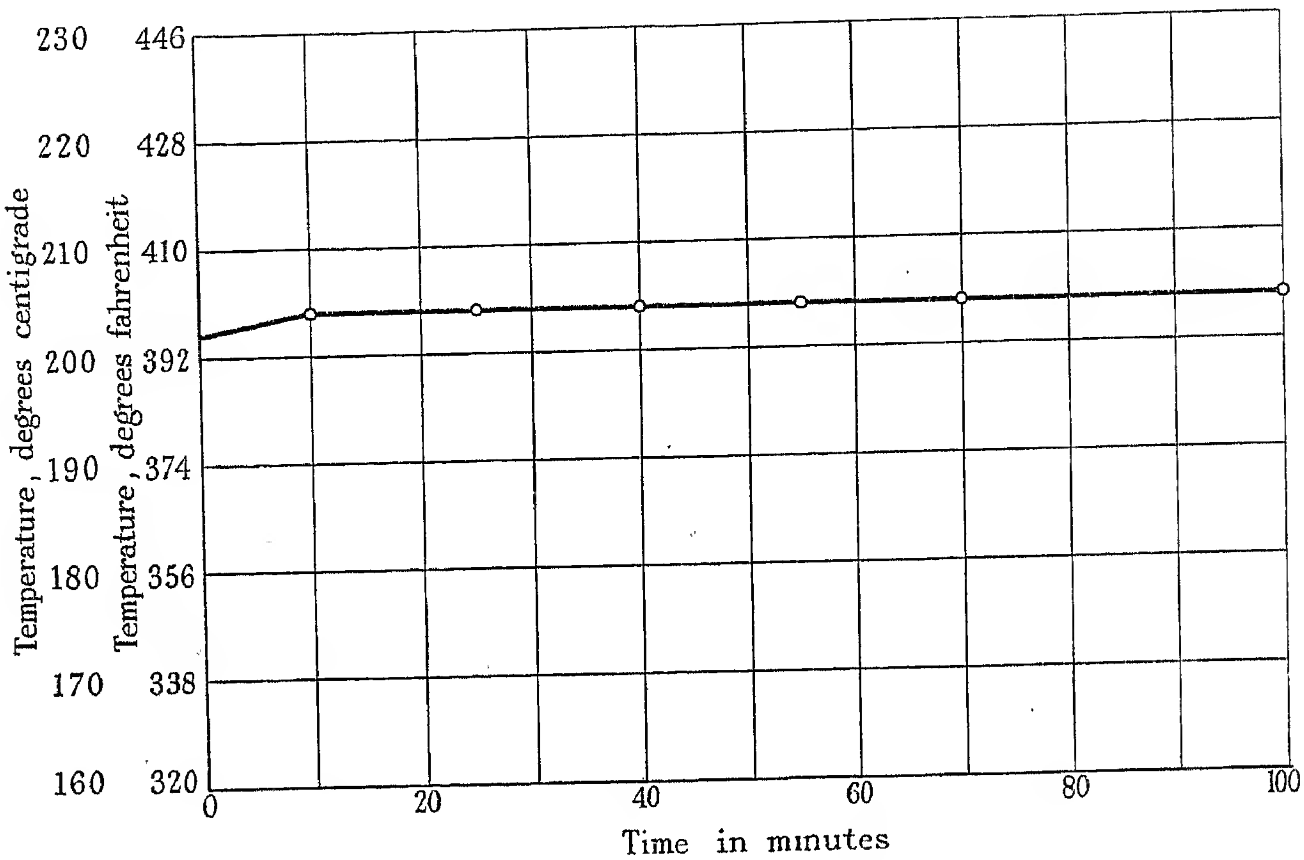


Fig. 11.—Die temperatures recorded on the Henley lead-extrusion machine.

2 to 3 % around the circumference is adequate. This, of course, means not only a superior product but a very considerable saving in lead.

The question of crystal structure is of great interest, as the appearance of the polished and etched section forms a useful criterion of the properties of a cable sheath. Sections cut at frequent intervals along a continuously extruded cable sheath show a remarkable uniformity of structure.

Quality of Product

The quality of the cable sheath produced on a continuous lead-extrusion machine can be judged from the various points of view from which the demerits of the hydraulic press product were analysed in an earlier section.

Taking first of all oxide inclusions, nothing much more can be said than that they do not exist. The examination of sections cut from hundreds of cable sheath samples has not revealed a single case of oxide inclusion, such as is found from time to time in cable sheaths from the hydraulic press. In no case has it been found possible in the modern machine to trace in the grain structure any oxide layering.

Then as regards stop marks, owing to the continuous running of the machine they are obviously absent, but even when a stoppage does take place, distortion of the pipe at the die does not occur. There is no " breathing " of the die relative to the point, and no change in the " weir " effect, i.e. the spilling of the lead over the die lip, with the result that the pipe is not strained locally on restarting.

(5) LEAD MELTING

Normal Methods

There are many designs of lead-melting equipment in use, depending on the individual ideas of different manufacturers. In general they consist of an open-topped metal pot of cast iron, cast steel, or wrought steel, supported on a stand within a firebrick-lined furnace and fitted with burner facilities suitable for the particular fuel used. The upper part is usually covered in for reasons to be discussed later, and arrangements are included for charging the lead pigs, removing the surface dross, and controlling the flow of molten lead to the

press. An important factor to be observed as an introduction to continuous lead melting and extrusion is that the ordinary lead pot to feed a hydraulic press must be capable of supplying sufficient molten lead at one draft to fill the lead container. The normal capacity of a lead-melting pot in a modern cable factory is about 4 480 lb., while pots are in use which will melt up to 10 000 lb. at a time.

Fig. 12 shows the main features of a typical gas-fired lead-melting pot as used in conjunction with a hydraulic sheathing press. The cast steel pot, 3 ft. 6 in. long by 1 ft. 6 in. wide, is supported inside a firebrick enclosure in which gas or oil burners are housed. The products of combustion from the furnace are carried up over the surface of the molten lead within the sheet metal cowl on their way to the chimney, so providing a semi-inert atmosphere to minimize surface oxidation of the lead. The pigs of lead are fed into the furnace through the trap shown on the right-hand side, and the molten lead is drawn off as required through the hole at the bottom of the pot. An inspection hole in the side of the hood provides access to the surface of the lead for removal of dross.

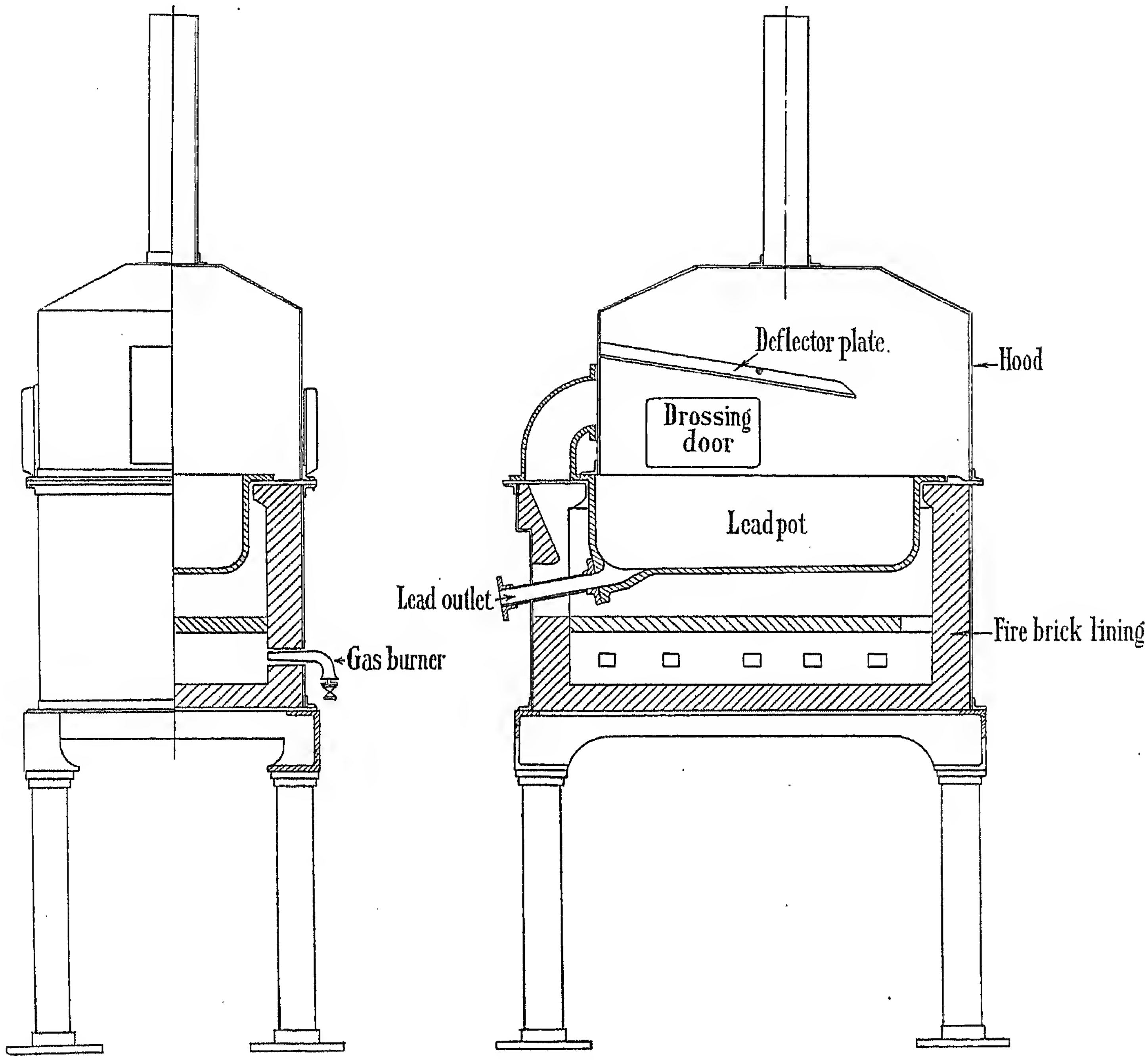


Fig. 12.—Lead-melting pot and furnace.

Oxidation

At the temperatures employed in the lead pot (700° F. to 750° F.) the surface of the lead in contact with the air rapidly oxidizes, with several obvious disadvantages. From modern knowledge of the metallurgy of lead pipes and cable sheaths it is clear that the presence of oxide in the pipe wall is deleterious, and although such oxide may actually form in the hydraulic press after the lead has left the pot it seems reasonable to prevent the formation and entry of oxide into the lead at the source. To a certain extent the oxide is soluble in the lead, and, moreover, the rise and fall of the surface of the molten lead, as it is drawn off and recharged, results in the oxide sticking to and travelling down the inner surface of the pot, requiring frequent emptying and cleaning.

A second disadvantage of oxidation is the waste of lead so incurred. It is no uncommon thing for drossing to result in a loss of $1\frac{1}{2}$ to 2 per cent of the total lead consumption, which in itself may be equivalent to hundreds of pounds sterling per annum in a normal factory, and on the total consumption of this country a loss of £20 000 to £30 000 per annum.

Another and important disadvantage of oxidation in

lead-melting pots arises out of the fact that certain alloying metals, which are added during melting, oxidize more readily than the lead itself, with the result that the correct percentage desired in the finished cable sheath is not achieved and the more expensive metal is wasted. Drossing also involves a labour charge and the provision of access to the surface of the molten metal to enable it to be skimmed.

In an attempt to mitigate the drossing nuisance many ideas have been suggested and tried out. In the furnace already shown in Fig. 12 the products of combustion from the gas burners are conducted by means of a deflecting hood over the lead surface and, being deficient in oxygen, reduce the amount of oxidation. In other schemes the lead surface is protected with an inert gas, carbon dioxide or nitrogen, or a reducing gas, such as hydrogen, and in one case by a vacuum. One ingenious and effective method introduced recently (Patent 424130, Callender and Hill) employs an iron float on the surface of the molten metal, designed in such a way as to keep the metal covered and protected from the atmosphere under normal conditions and to open up with the weight of a pig which thus passes through into the pot.

Table 1

Heat Units to Melt, and raise to 420° C., 1 ton of Pig Lead in Various Types of Furnaces.

	Electric heating	Gas heating	Theoretical value
Expressed in electrical units ..	56 to 77·2	54·6 to 165	25·9
Expressed in therms ..	1·9 to 2·63	1·86 to 5·62	0·88

Heat Economy

As continuous extrusion of lead cable-sheaths makes also the operation of lead melting a continuous process, improved economies become possible and it is desirable, therefore, to consider the theoretical optimum condition and to see to what extent the usual types of furnace approach this condition.

When lead is converted from the cold pig, heated to melting point, melted, and then raised to a higher temperature of 420° C., the specific heat (0·04 calorie per gramme per deg. C.) must be supplied from, say, 20° C., to the melting point (327° C.), and again from 327° C. to 420° C., and the latent heat of fusion, 6 calories per gramme, added.

The energy required per ton of lead

$$= [(400 \times 0{\cdot}04) + 6]453 \times 2\,240$$
$$= 22{\cdot}3 \times 10^6 \text{ calories}$$
$$= \frac{22{\cdot}3 \times 10^6 \times 4{\cdot}18}{10^3 \times 60 \times 60} \text{ kWh}$$
$$= 25{\cdot}9 \text{ kWh}$$

which corresponds to $2\,240/25{\cdot}9 = 86{\cdot}5$ lb. of lead per kWh.

With gas heating, 1 therm = 29·4 kWh so that the heat theoretically required to melt, and raise to 420° C., 1 ton of lead by gas is 0·88 therm, which corresponds to 2 550 lb. per therm.

An examination of the performance of a number of different lead-melting furnaces shows that the tested fuel consumptions vary considerably from one type to another. Table 1 shows the order of actual values compared with the theoretical figure.

(6) CONTINUOUS TUBULAR LEAD-MELTING FURNACE

Construction

The adoption of continuous lead-extrusion makes possible considerable improvements on former methods of melting lead. In the first place the sudden demands for a large quantity of molten lead made by a hydraulic press do not occur and the lead need only be melted and supplied at the same rate as that at which the finished cable sheath is extruded from the machine. This naturally reduces the size of the lead pot, and with it the heat losses. At the same time this factor facilitates the adoption of means for preventing oxidation of the lead and makes automatic feeding a fairly simple proposition. Alongside the continuous lead-extrusion machine has been developed, therefore, a continuous lead-melting furnace with automatic pig magazine and elevator.

Fig. 13 shows the general form taken by the furnace and accessories. The furnace tube proper A is of D-section set up on an angle-steel support F at an inclination of about 45° to the horizontal and is divided into three portions—an entrance lock between two gas-tight doors K and L, a central portion where the solid pigs slide down after one another into the molten metal, and a bottom chamber where the temperature of the lead is controlled on its way to the extrusion machine. The lower end is connected to the machine by a lead valve M by which the flow of lead may be stopped or, alternatively, diverted for emptying the furnace.

Two separate heater systems are applied to the tubular container, an upper one N for bringing the pigs up to the melting point and actually liquefying them, and a lower one B which heats the lower chamber. The final temperature of the lead is thermostatically controlled through the supply of heat—electric or gas—by means of an immersion thermostat. The amount of lead admitted through the entrance lock at the upper end of the furnace is controlled by the operation of a mechanical trigger P actuated by the passage of lead pigs. This operates a switch or air cock which in turn opens and closes the admission door L through the solenoid or door engine shown.

Pig Magazine and Elevator

The handling of lead pigs from the storage stack in the shop is not one which can be effected entirely by automatic means, but by the arrangements devised in connection with continuous melting and extrusion a distinct advance has been made in this direction.

The pig-handling plant associated with the continuous melting furnace consists of a magazine H carrying up to 20 pigs which discharges automatically into an elevator J, which in turn feeds the furnace as and when more lead is required. From the placing of the pig on the magazine no further handling or manual control of the lead is

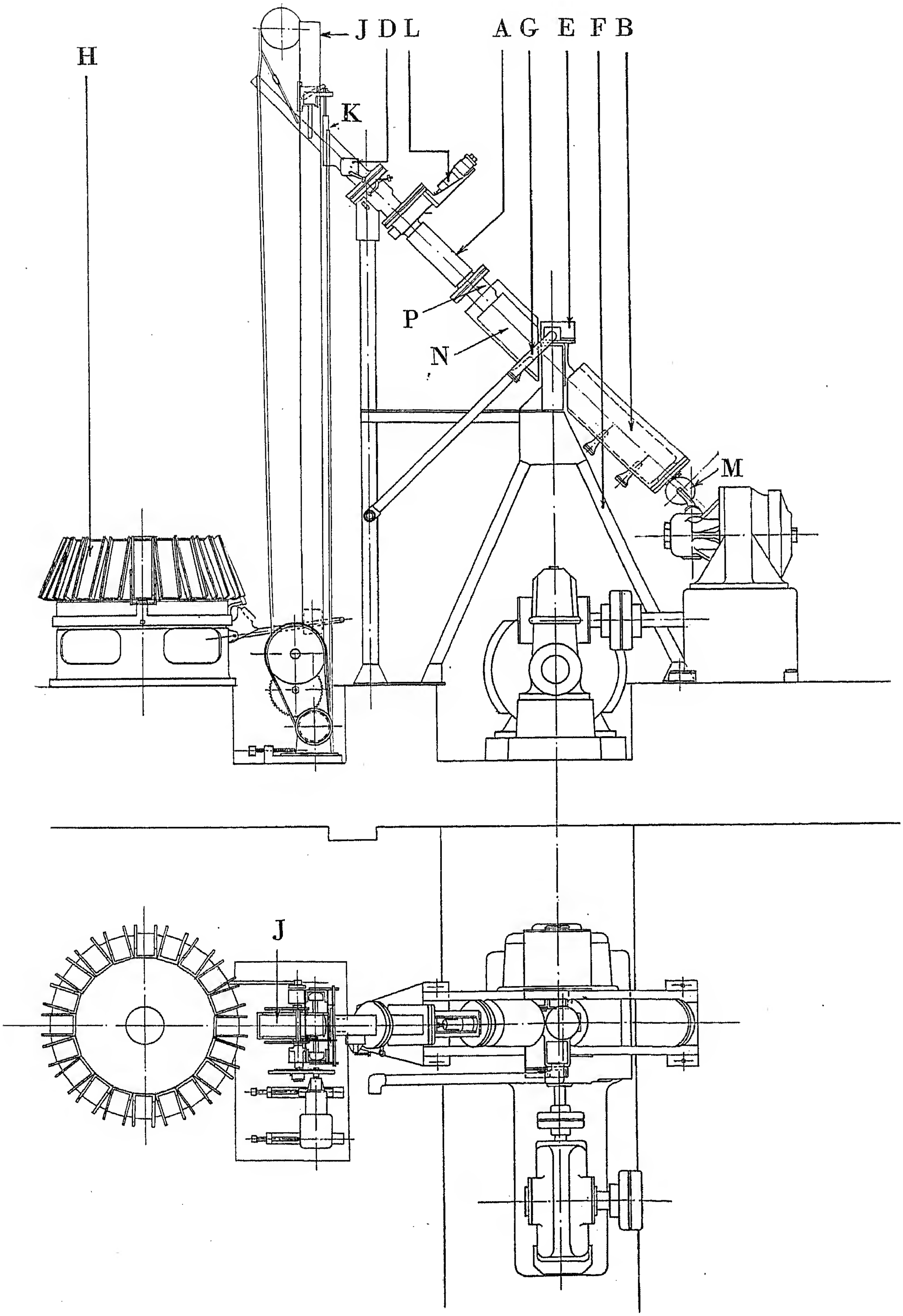


Fig. 13.—Arrangement of tubular lead furnace for Henley lead-extrusion machine.

called for until the drum of finished cable is removed from the front of the machine.

The pig magazine H consists of a circular carriage in the form of a truncated cone rotatable about a vertical axis and having on its outside sloping surface a series of cradles in which the pigs are placed. The magazine operates in conjunction with the elevator in such a way that each time the elevator descends the magazine is rotated automatically the distance between two pig cradles and a pig is discharged from the magazine into the elevator.

The complete operation of the furnace and feed will be described in connection with Fig. 13. Let us assume the following conditions:—

(i) The molten lead in the melting chamber is at a normal level.
(ii) There are the remains of two pigs in the melting chamber.
(iii) Both doors of the gas lock are closed, and there is a cold pig in the lock.
(iv) There is a further pig in the elevator cradle which is at the bottom of its travel.
(v) The pig magazine is full of pigs.

When molten lead is withdrawn for the extrusion machine from the lead valve at the bottom of the furnace, the level of the lead falls and with it an iron float in the melting chamber which operates a mercury switch E connected to the heating circuit. The resulting increase of heat melts more lead to restore the level, and the solid pigs slide down the tube by their own weight. The release of a mechanical trigger P by the passing of the melting pig opens the lower door of the gas lock by means of either a solenoid or a pneumatic door engine, depending on supplies available, and a pig slides out of the gas lock into the melting chamber. As the pig passes out of the gas lock it operates switch D, so starting the elevator motor and causing the cradle already charged with the next pig to rise to the top of the furnace, where it automatically opens the entrance door K and discharges into the gas lock. This resets switch D, reversing the elevator motor and sending the cradle down again ready for a further pig from the magazine. When the elevator cradle arrives back at the bottom of its travel it triggers off the pig in the sloping holder on the magazine opposite. The pig slides down into the elevator cradle and the whole cycle of operations is complete, to be started again as soon as the level of the molten lead in the melting chamber falls sufficiently. The rotation of the pig magazine is effected by a pawl connected to the rising and falling elevator and operating on a ratchet which brings the next pig into position each time the elevator rises and falls.

(7) AUTOMATIC CABLE TAKE-UP

The author has so far described the machines and methods for applying a lead sheath continuously to a cable, and the furnace with feeding arrangements for supplying the machine with molten lead. Attention has also been paid to the handling of the cable as it emerges lead-sheathed from the extrusion machine, as inefficient reeling-up may easily prevent full advantage being taken of the adoption of continuous extrusion.

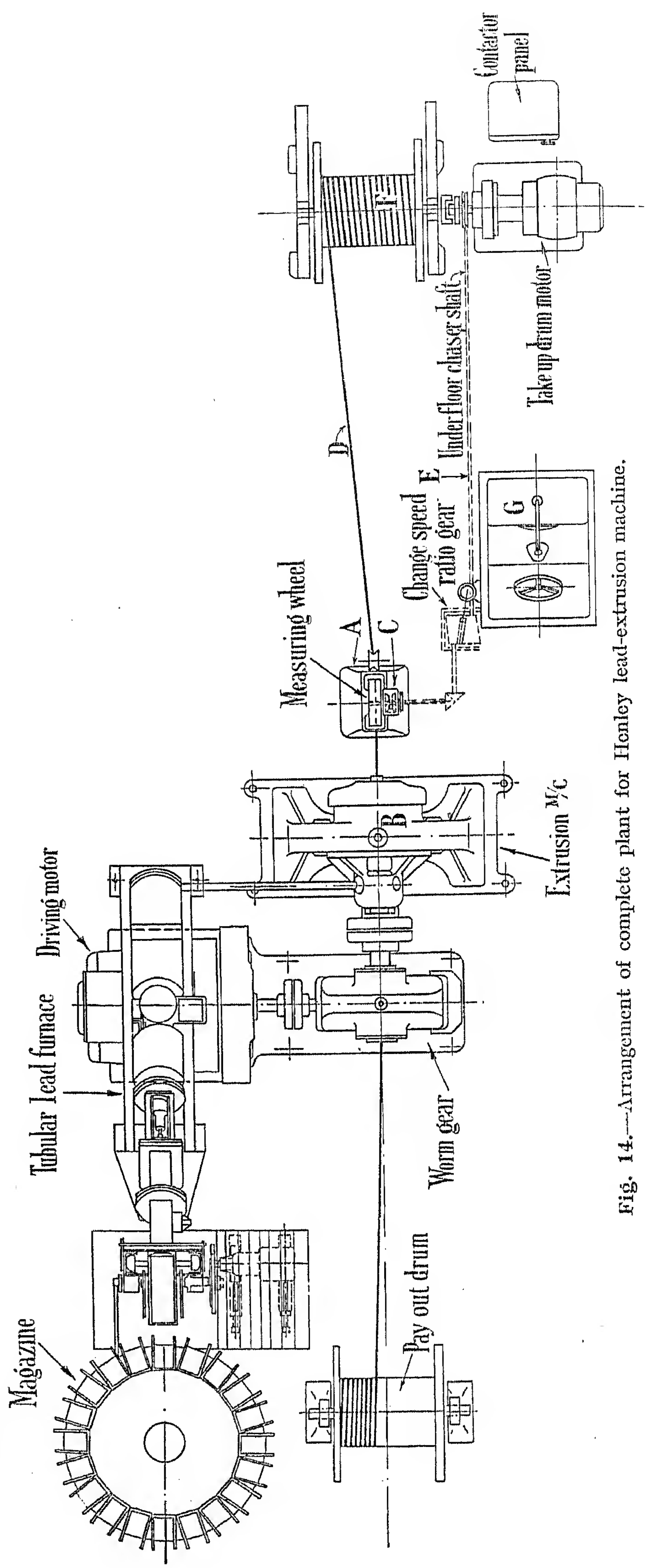


Fig. 14.—Arrangement of complete plant for Henley lead-extrusion machine.

The usual practice for reeling cable in front of a lead press is to employ a mechanically driven drum driver manually controlled by an attendant who watches the cable going on to the drum and adjusts the speed of rotation of the drum in such a way as to take up the slack and at the same time to avoid undue stretching of the cable. In some cases the man guiding or flaking the cable-turns on to the take-up drum controls the speed of rotation at the same time by a pedal control.

Various attempts have previously been made to synchronize the rotation of a take-up drum with the speed of extrusion from the press, but the method developed by the author in conjunction with the running of the continuous lead-extrusion machine may be of interest. The principle of the method, which is quite simple, is to employ a measuring wheel driven by the cable at the extrusion machine, which is connected to the take-up drum through a differential device. The arrangement corrects the speed of the take-up motor through electrical contacts so long as there is any difference between the speed of the cable going on to the drum and the speed of the cable emerging from the extrusion machine.

The principal part of the device consists of the differential pedestal A shown in Fig. 14. This consists of a cast-iron pillar standing on the floor in front of the extrusion machine B and carrying the differential gear C with control contacts at its upper end. The measuring wheel, rotated by friction with the surface of the emerging cable D, drives one of the two side wheels of a simple bevel-wheel differential gear. The second side wheel carried loosely on the same spindle is driven by a flexible shaft running up the centre of the pedestal from the floor, where it is coupled by means of a detachable coupling to a light shaft E running under the floor to the motor driving the take-up drum F. For reasons to be explained later, the floor shaft runs via the main control pedestal G to the extrusion machine.

The floating carriage in the differential gear is friction-coupled to two electrical contacts which act as accelerating and retarding contacts respectively in a circuit controlling the take-up drum motor. When the measuring wheel is rotating faster than the chaser wheel driven by the underfloor chaser shaft from the take-up motor, the floating carriage, operated by the coupling pinion between the measuring and chasing wheels, rotates and holds down the accelerating contact. As soon as the driving motor has speeded up sufficiently, the floating carriage returns to the neutral position and the conditions are stabilized. Similarly, should the extrusion machine be slowed down for any reason then the chaser wheel in the differential rotates the floating carriage in such a direction as to close the retarding contact, which reduces the speed of the take-up motor the requisite extent.

In order to accommodate small differences or to make a permanent change in the quantity of slack cable between the extrusion machine and the take-up drum, the chaser shaft is passed through change-speed ratio gear in the control pedestal manually operated by the machine driver. This same mechanism can be employed for adjustment between flakes of different diameters on the take-up drum.

(8) COMPLETE PLANT FOR CONTINUOUS CABLE SHEATHING

Layout

Fig. 14 gives a suitable layout for a complete continuous cable-sheathing plant with continuous lead-extrusion machine fed by a continuous tubular lead-melting furnace with pig magazine and elevator and provided on the cable take-up side with automatic control of the drum speed.

The cable to be sheathed comes from the drum on the left, passes through the machine and, after sheathing, is reeled up on the right-hand drum. It will be observed that the control pedestal is in such a position that the driver has a complete view of the whole plant, including the lead melting.

Operation

The operation of the plant is carried out almost entirely from the control pedestal, and the attendant need rarely leave this central point. Once the pig magazine has been charged with 20 pigs no more attention is required at the melting end except once or twice an hour when the magazine must be filled up again by labourers who in the meantime may have been employed on other duties. Their intermittent attention makes no difference to the regularity of the melting process.

While the cable is running the driver may have minor correction to make to the controls. At the end of a length of cable he stops the extrusion machine, or allows it to crawl very slowly, while the drum is changed and the next length threaded up. The connection of the front end of a new length to the take-up drum is, of course, a simple matter, as the drum is rotating empty at the correct speed when the man brings forward the end of the new length. Once the cable is attached, speeding-up the extrusion machine automatically speeds up the take-up drum and the whole plant is controlled by one handle.

ACKNOWLEDGMENT

In conclusion, the author wishes to express his indebtedness to the directors of the Henley Extrusion Machine Co., who have allowed him to publish the information contained in this paper.

DISCUSSION BEFORE THE INSTITUTION, 3RD DECEMBER, 1936

Mr. P. V. Hunter: It is too often alleged against this country that we are not taking our full share in the new developments which are being made in engineering, and particularly in electrical engineering. This paper describes, however, a development of first-class importance in a field where it has been obvious for a long time that something of the kind was urgently needed. This development is essentially a British one, because not only is it due to the work which the author has put into the design of the machine, but also it has been made possible very largely by recent developments in this country in the production of special steels for withstanding heavy mechanical stresses under high temperatures.

The first thing that I should like to impress on those

who are to use these machines is that the inventors and developers have undoubtedly claimed too much for them. It is desirable not to pay too much attention to the statement made by the manufacturers that these machines can deal with all kinds and classes of alloys, because at present they cannot. I advise anyone who purchases one of these machines to confine it in the first instance to the extrusion of plain lead sheathing or pipe. The stresses set up by the extrusion of plain lead in such a machine are high enough for the moment, and we should not yet try to extrude the harder alloys. A very large proportion of every cable maker's output is sold with plain lead coverings and, even if this machine were always restricted to coverings of plain lead, it would still have an extremely large and useful field of application.

Another point that I would impress on purchasers of these machines is that they should not take too seriously all the statements that are made about their behaviour in regard to the production of irreproachable tube. Extrusion machines can turn out eccentric lead tube much in the same way as is done at times by other machines. I am convinced that there is no reason why they should do so, however; and when the technique of the operation of these machines is as well understood as is that of the reciprocating press there will be no question of anything but truly concentric lead sheaths being produced. When these machines are working normally they undoubtedly produce sheaths of admirable quality.

Mr. F. O. Barralet: The prospect that the author's machine gives of obtaining cable-sheaths without defects, and of more economic means of production, is extremely attractive to the user. The former point is perhaps of the greater importance; nevertheless we may hope that cheaper production will also result in a lower cost to the user.

I cannot help thinking that no one but an engineer would have thought of this method of producing a cable-sheath. To the pure metallurgist, I imagine, the idea of treating metal like so much sausage meat would be almost repulsive. Where a metal is subject to the conditions of stress and temperature that must exist in this machine it might be anticipated that unexpected metallurgical effects would occur and produce undesirable results. This does not seem to be the case, however, and the photographs of the samples given in the paper seem to prove conclusively that the structure of the extruded metal is quite normal and of remarkable uniformity. I should like to mention, however, that in a sample of lead sheath produced by a continuous machine, which we examined some time ago, we did not find quite the same perfect crystal formation all the way round the circumference. Four sharp radial lines could be seen, showing that an impression had somehow been left on the structure of the lead, apparently owing to the division of the lead stream by bridge supports. I do not suggest that these marks indicate a defect, because the bursting stress of this part of the sheath was absolutely satisfactory, and moreover the burst did not occur along these lines. The presence of the lines, however, is puzzling to me, and I shall be glad to know whether the author has any metallurgical explanation of their presence. They seem rather thicker than ordinary crystal boundaries. The sheath as originally etched did not show those markings; it was only when it was very deeply etched that they showed up. Their presence is interesting in view of the fact that in the absence of oxide one would expect crystals actually to interlock across the boundaries of the uniting lead streams.

The conditions which arise in connection with the extrusion of lead and which affect the welding-up can, I think, be rather well illustrated by quoting from a paper* written a good many years ago on the crystallization of metals, and, in spite of the elaborate theories of plastic flow in metals which have been brought forward since, the following words are still true: "Crystal growth or recrystallization will not take place unless metal has been subjected to plastic deformation. . . . Neither crystal growth nor recrystallization will take place after plastic deformation unless the metal is heated to a certain minimum temperature for a certain minimum time." It seems to me that in any lead press, quite apart from whether there is oxide present or not, the condition may arise in which these fundamental requirements may not be met. The paper seems to suggest that the continuous press is almost incapable of turning out an imperfect sheath, but I should like to ask the author what happens at the two extreme limits of the extrusion conditions. It is clear that, if the lead is allowed to freeze, the machine will jam. If the lead is too hot the impeller, I presume, turns round and no lead comes out. What would happen, however, in extruding sheaths at temperatures too near these upper and lower limits? It seems to me that in the case of the latter the effect might be met with that occurs with the ordinary hydraulic press, where if the lead is too cold it may fail to unite when it passes a bridge or any other structure which divides it, quite apart from whether any oxide is there or not. The term "cold shut," which is sometimes used in connection with this defect in lead sheath, may be a perfectly fair description of the effect, indicating that the temperature conditions for crystal growth referred to earlier have not been met.

The number of faults due to splitting of lead sheaths in this country is not so high as formerly, owing to the fact that lead-press technique and the conditions leading to the production of the defect are better known. Very few examples of split lead sheaths have come to my notice in the last few years. I was, however, surprised to read in a German periodical last year that the very frequent occurrence of split lead sheaths in German Post Office communication cables had been causing concern for the last 8 or 9 years; 176 cases were quoted of lead cable-sheaths failing in practice owing to this defect. The faults were distributed quite indiscriminately between lead and the various lead alloys which had been used.

One of the most striking features of the author's machine is its extremely small size as compared with the ordinary lead press. This avoids a great disadvantage of the hydraulic press, namely that its large mass and consequent thermal inertia makes accurate temperature control very difficult. The temperature-

* H. C. H. Carpenter and C. F. Elam: "Crystal Growth and Recrystallization in Metals," *Journal of the Institute of Metals*, 1920, vol. 24, p. 83.

gradient curves which are given in the paper bring this out very markedly, but I am rather surprised at the very wide variations shown in the case of the hydraulic press.

I do not quite understand what the author means by layering and the need for the precautions that are apparently taken, in spite of the absence of oxide with this machine, to avoid this trouble. Is it possible for defects due to layering to occur in the wall of this sheath, even though oxide is absent?

One advantage which a machine of the type described in the paper appears to possess over the hydraulic press is the absence of conditions leading to segregation of alloy constituents. In the hydraulic press, since the charge solidifies as a comparatively large ingot there is a chance for segregation to occur. The mass of metal that actually solidifies in the continuous machine, however, is small and continuously churned. I should be interested to know whether the author claims any superiority, with regard to uniformity of composition, for alloy sheaths extruded by his machine.

For the purpose of the sheathing of submarine cable the author's machine has very great advantages. It obviates stop marks, and the mere fact of being able to work continuously presents advantages which need little comment.

The idea of being able to extrude sheath of very exact thickness appeals to me very much. I have had in mind for some time the possibility of being able to construct a cable in which the lead or lead-alloy sheath would be very much thinner than the ordinary sheath used, the lead being employed merely as a moisture-proof barrier to prevent the water getting into the cable, and being covered with some organic material as a further protection. The object of this form of construction would be to produce a cheaper corrosion-proof cable. Its success, however, would probably depend on the uniformity of thickness with which such a thin sheath could be extruded, and the author's machine seems to give some hope of attaining this uniformity.

Mr. T. R. Scott: It is interesting to recall that the process for the lead covering of cables was first patented in 1845 and was first exhibited at the Exhibition of 1851. A month or two ago I had the privilege of inspecting one of the historic presses which took part in the early development—that of François Borel. My feeling as I examined the press was one of real admiration for the pioneers of those days, who produced a process which ever since has carried the burden of sheathing the world's lead-covered cable system, both communication and power. That process has scarcely been challenged until the present year.

The author would obviously advise that the cable makers of this country and of the world at large should scrap their existing lead-press equipment and participate immediately in the economic advantages and technical benefits of the continuous extrusion process. I think that before such replacement can be justified he must amplify his paper and answer four fundamental questions: (1) How many faults, out of all the faults which occur on cable sheaths, are due to the intrinsic principle of the press operation? (2) How many fewer faults will the screw press produce? (3) Taking the average quality of the lead pipe which is produced to-day, to what extent will this be improved by the pipe produced by the screw press? (4) Lastly, what other alternatives are there in place of the screw press referred to by the author?

The author deals only with my first question in his Introduction, where he infers that the majority of sheath faults are caused by the reciprocating lead-press technique. I submit that he ought to have indicated that, out of the grand total of lead-sheath faults, only comparatively few are due to the press itself. From the grand total of sheath faults we must subtract all those due to corrosion, all those due to vibration, and all those due to mechanical strains and stresses set up, for example, in heavily-loaded cables in ducts. The remainder can be directly attributed to the press. In the United States, where conditions for the working of cables are very severe—much more severe than in this country—the number of sheath faults directly attributable to the press is comparatively a small proportion. Taking one comprehensive analysis, I find that, out of the total number of sheath failures examined (626), those attributable to the lead press number only 65. Analysing those 65, I find that those attributable to the intermittent action of the hydraulic ram (coupled with oxidation, etc.) total 26. The screw press, therefore, at the very best can eliminate only 5 to 10 per cent of the sheath troubles with which the cable world is afflicted at present. It is to be admitted that the results obtained by cable makers with lead presses of the present type are obtained only by very careful attention to technique and by the selection of skilled and trained operators with long experience. From that point of view, I agree that the press put forward by the author undoubtedly is superior from every economic angle. The question for the moment, however, is the question of technical merit. It is true that, theoretically, continuous extrusion can produee a perfect sheath, and that theoretically the hydraulic press cannot produce a perfect sheath. I submit, however, that the question really is: What is the probability that either of these processes will produce a perfect sheath? The probability of the hydraulic press not producing a perfect sheath is dealt with fairly fully by the author, but the probability of the screw press or the continuous-extrusion press not producing a perfect sheath has not been dealt with so fully.

In producing sheathing by continuous extrusion, something has to be sacrificed. The nature of the sacrifice differs according to the type of continuous extrusion put forward. As has been mentioned by the author and by Mr. Hunter, there are two types of continuous-extrusion press at present being developed in this country. Both types, however, must depend for the quality of their sheath on the flow of the lead in the press and on the control of the temperature of that lead flow. It is possible, therefore, that failure of mechanism, or lack of care on the part of the operator, will result in defects which constitute a fairly large departure from the ideal sheath.

As Mr. Hunter said, there is no doubt that when the technique of presses of this type has been mastered there will be considerable probability of producing sheaths which will approximate far more closely to the ideal than at present. Until experience and practice have developed the technique to that stage we must accept

continuous extrusion by screw presses as an alternative method to that at present employed, accepting the economic gain afforded only when we are assured that by so doing we are not risking a decline in quality.

Mr. K. Gray: I am a manufacturer of lead pipe, and I should like to say that my experience indicates that the presence of oxide in the pipe wall accounts for certainly 50 per cent of the pipe failures. The presence of oxide is indeed a fundamental and serious difficulty with regard to the production of a good lead pipe, and it cannot be avoided by the ordinary type of extrusion press. Certain patents have been taken out for a process by which it can to some extent be avoided, but to use this process involves the payment of a royalty, which is very objectionable when one has a low-priced commodity for sale.

Turning to the question of temperature control, the normal type of lead press causes us to extrude our pipe vertically, either up or down. We cannot at the present time extrude it horizontally. During the process of manufacture the lead pipe does not come rapidly into contact with a cold core, as happens, of course, when a cable is being covered, and therefore the pipe temperature is sometimes extremely high. We also come across a curious difficulty which rather accentuates the diagram shown in Fig. 10. When we start to extrude we have a very short length of core, possibly less than ½ in., projecting through the die. As the extrusion goes on, that core steadily comes farther and farther through the die, and in those cases where normal presses are employed a ½-in. 7-lb. lead pipe passes through the die 100 times as fast as the core does. We therefore have a new factor which has a profound effect on temperature, and that is the friction between the pipe itself and the core as the pipe slips over that core. It is common to find that we are getting well above 470°–480° F. halfway through the extrusion charge, and there is no means of controlling this rise in temperature. As we get near the bottom of the charge the speed and the temperature begin to fall, but the great difficulty about it is that we have no control of the temperature; we are producing the pipe in a vertical direction, and we have to bend it over a pulley very close to the press. Most of the presses send the pipe upwards, and when the pipe is 6 ft. or less away from the top of the press from which it comes it has to turn over a pulley; this turning introduces an entirely new and very serious factor. Most lead pipe has a small tin content, and I am certain that it is not safe to start to coil a pipe which has been extruded from an ordinary lead-pipe press until the temperature has fallen below the melting point of tin. I believe that the transverse cracks which are very common are largely due to the fact that the pipe has been coiled when the temperature was still above the melting point of tin.

If we can produce the pipe with a controlled temperature and in a horizontal direction, we can do just what we like with the pipe before starting to coil it. If we are producing the pipe vertically from an ordinary hydraulic extrusion press and we section that pipe before it gets to its first turning-point, we find that we have a very well-defined uniform structure. Passing the pipe over the pulley upsets this condition; the outside of the pipe is thereby put in tension, and as the temperature is adequate a crystal growth occurs. A little zone with large crystals on the outside of the curve is produced. Between the first pulley and the second pulley the pipe sags, the under side is in tension, and a similar growth therefore begins on the bottom of the pipe. An uneven crystal structure results in a pipe which is liable to crack. If we produce the pipe horizontally we can quench it if we like; the coiling can be carried out at a suitable temperature, and in that way we are able to get a very much better article than is otherwise possible.

Mr. H. J. Allcock: It is doubtful whether the author's contention, that the technical advantages to be obtained by the use of the continuous-extrusion machine will be more important than the economic advantages, can be upheld in practice. It is not questioned that there may be a considerable increase in output per man-hour owing to the more continuous nature of operation and the possibility of more complete mechanization of the whole process, but the picture which the author paints of the present state of the process when employing non-continuous hydraulic presses is much too gloomy. The number of cable failures directly attributable to non-continuous extrusion is very small, and is growing smaller year by year, the advances of technique in the use of the non-continuous hydraulic press having made possible this improvement.

The two main requirements are the prevention of oxide inclusions and the production of perfect welds in the resulting lead sheath. The first (on which the second is, to some extent, dependent) may be achieved by methods indicated in the paper for the prevention of the formation of oxide on the surface of the molten lead in the melting pot, combined with a suitable design of pot, valve, and lead-in to the press. Apart from this, the production of a perfect pipe in a non-continuous press depends to a large extent on the proper welding of the new charge of lead to the residue of the old charge in the lead-press container. The usual procedure is to extrude a large part of the charge, leaving a small part in the bottom of the container, and to pour the new metal into the container through an open chute, so that it gradually fills up the container. If this is done, imperfect welding of the two charges may result, and this imperfect welding may still persist even in the pipe after extrusion. An improved method is available, however, in which the whole of the molten metal of the new charge is passed over, and melts, the surface of the old charge, so that the two charges unite and solidify as one, and no imperfect welding is present to appear in the resulting pipe.

Again, the question of temperature control is important; and, in this connection, it would appear that Fig. 10, where the maximum temperature is of the order of 30 per cent above the minimum temperature, is hardly typical, a figure of 10 per cent being more of the correct order.

It cannot be agreed that the stop mark is inherently a source of weakness in the cable, either in the sheath or in the dielectric. In fact, owing to the change of crystal structure at this point (larger crystals being normally obtained owing to the self-annealing which takes place) and the slight thickening which normally occurs, the pipe is generally stronger at this point than elsewhere along its length, although the ductility may be slightly reduced.

This has been shown practically by taking a number of empty pipes with stop marks and subjecting them to sufficient internal pressure to burst them; when it has been found that the burst has invariably occurred at some point remote from the stop mark. There is also a remarkable freedom from failures in service due to stop-mark defects. Again, the extra heat applied to the short length of cable standing in the press seems to have no deleterious effect on the dielectric of the cable. It should be pointed out that any particular part of the cable does not stay in the press for more than a few minutes, owing to the fact that the cable is inched along during the standing period. I have turned up records over a number of years and have been unable to discover any case of failure on test, or in service, which could be directly attributed to deterioration of the dielectric due to the cable standing in the press.

The author implies that his extrusion machine can be stopped and started at will, without change of sheath structure and dimensions. If this is so, it is a most important point in its favour; because, even with such a machine, there must be times when it is necessary to stop extruding to change drums, to get new cable into position for sheathing, and to make minor adjustments; and unless these pauses in extrusion can be made without modification of the sheath the machine will not be of such value as would at first appear.

Finally, can the author state what is the normal time for changing dies, from the commencement of the operation of changing to running with new pipe of the correct dimensions?

Dr. W. G. Radley: When one sets the author's continuous-extrusion press alongside the old type of extrusion press, the latter appears to be so cluttered up with disadvantages, theoretical and practical, that it is surprising that so many hundreds of thousands of miles of lead-sheath cable and pipe have been successfully extruded in the past. We must admit, however, that the old type of machine has a fairly wide tolerance to operating conditions. The variation of die temperature may be taken as an example. Fig. 10 suggests that lead-sheath cable was extruded with a variation of die temperature of about 45 deg. C. With careful operation this variation should, however, be considerably reduced. Some records which were taken of the temperature of the die during the extrusion of about 30 miles of submarine cable, representing a very large number of different charges, indicate a variation which was at no time greater than 20 deg. C. Incidentally, I should like to ask the author whether Figs. 10 and 11 both refer to pure lead or both to the same alloy. If they do, the operating temperature of the press which he has described seems to be very much higher than that of the non-continuous hydraulic press.

Regarding the disadvantages and dangers which are likely to arise during the stoppage of the old type of press for recharging, metallurgical effects may be caused by prolonged local heating at one spot. Such effects have been feared, especially with alloy-sheath cables. My views are not quite those of Mr. Allcock, because I have always been taught to associate grain growth in lead and its alloys with loss of ductility and to fear that where grain growth takes place local weakness may also be found. With that in mind, some experiments were made some time ago in which a number of strips, some of pure lead and some of the alloys which are commonly used, were annealed at various temperatures for a period of 15 minutes. This is rather longer than the time for which one expects a press to be stopped. On examining the crystal structure before and after annealing, it was found that with an annealing temperature below 200° C. very little grain growth took place in lead containing 1 % antimony, or 0·25 % cadmium and 0·5 % antimony. At temperatures above 200° C., the grain growth was rapid. In the case of tellurium lead the grain growth was negligible when the alloy was annealed at much higher temperatures. This suggests that, if the die temperature is controlled so that it is not allowed to exceed 200° C. during the stoppage of the press, there are no sound metallurgical reasons for fearing that the stop marks need constitute points of pronounced local weakness.

I may have suggested that by careful attention to operating technique it is possible to produce satisfactory cable sheaths with the old-type hydraulic press. Nevertheless, the conception and development of the continuous lead-extrusion machine represent a very decided advance. It removes the possibility of many of the types of failure which have given trouble in the past.

Mr. W. McClelland: I should like to offer a few remarks based on long experience and responsibility for the life of lead-sheath cables on board ship, in places where they are necessarily subjected to severe vibration and very exacting conditions generally. Some representatives of manufacturers have stated that the number of lead-sheathing failures are few, but that is not borne out by my experience. I would refer in particular to two types of failures which occurred repeatedly over a number of years on many makes of cables. One was an annular break of the lead sheathing at various points along the length of the cable; the other was the splitting longitudinally of the lead sheath. The former was found to be due to the use of pure lead sheathing when subjected to severe vibration; this was remedied after long research by the use of a ternary alloy of lead-cadmium-tin. I believe that the majority, if not all, of the splittings longitudinally of the lead sheathing were due to the trapping of oxides along what I may term the seam or weld of the cable. Many discussions took place with makers of cables on this point, and they affirmed that the inclusion of oxides was the cause of this splitting defect.

The author's continuous lead-extrusion machine has therefore one great advantage, that, as the machine is not opened up for recharging with lead, it does completely exclude possibilities of the inclusion of oxides, and in consequence will eliminate much of the trouble to which I have referred. This new machine developed by the author should assist materially in the production of more satisfactory cables capable of surmounting the onerous conditions met with in ships at sea, but the lead sheathing should preferably be of the Admiralty ternary lead-cadmium-tin alloy and not pure lead as suggested by some speakers. Pure lead sheathing is, in my opinion, unsuitable for ship cables, or for cables fixed in positions subject to severe vibration.

Mr. S. R. Siviour: With regard to the results of past

experience referred to by Mr. Scott and Mr. Allcock, I want to suggest that it is not every engineer who reports to the manufacturer the failures which occur on his system. I agree that failures on lead sheaths are not numerous, but I can recall a few such failures. During the last fortnight I have taken out an 11 000-volt cable which had a very badly split lead sheath; such defects may take a long while to develop—this one took 20 years to come to light. What we ask ourselves is how many more cases there are in the ground developing towards that state.

Mr. F. W. Purse: With regard to Fig. 12, it comes as a shock to the electrical engineer to see that cable makers use a gas burner! There has been some talk of temperature control, and perhaps the author may be able to explain whether gas is so much better from the point of view of temperature control than electricity; I should have thought that electricity would give better control.

Messrs. Harry Hill and S. Beckinsale (*communicated*): The early part of the paper gives the impression that vertical lead presses produce very defective cable sheathing. Such, however, is not the case, for modern vertical lead presses are machines which, when used with properly-designed die boxes, dies, and satisfactory temperature control by means of thermocouples in the nose of the die, can produce featureless pipe if well-known metallurgical principles are observed and the old and new charges in the container are welded together. This welding is readily ensured by directing, by means of a vertical chute, the molten lead of the new charge on to the surface of the old charge. The "dirty" surface of the old charge can thus be washed completely away, and the impurities, which rise to the surface of the container, can be removed by skimming. This treatment removes the marks shown in Figs. 3(*a*) and 3(*c*).

Marks shown in the first and third photo-micrographs of Fig. 3(*b*) may not be oxide inclusions, but welds produced at too low a temperature. The presence of non-metallic impurity in such marks may be detected by annealing sections of the pipe at 250° C. for some hours. If the marks are merely a type of slip band and contain no non-metallic impurity such as oxide, the crystals grow over the marks and they are removed completely.

When comparing the merits of lead presses with vertical containers with those of presses with horizontal or practically horizontal containers, the problem of casting sound ingots in these must be considered. Casting a sound ingot in a vertical open mould is a much simpler problem than casting one in a practically closed mould placed in a more or less horizontal position. In the former, entangled air or gases can escape at the surface of the molten metal, while oxide also rises to the surface and may be skimmed off. In the horizontal moulds described, gases and non-metallic impurities tend to be trapped at the upper surface of the ingot. The vertical lead presses therefore start with a much sounder ingot than horizontal presses. In addition to this, when a horizontal press container is being filled the new charge slowly rises up the face of the old charge and dissolved or entangled gases tend to be released in this position. The lead also contains insufficient superheat to melt the face of the old charge, so that metallic continuity between old and new charges cannot be obtained. This defective junction of charges is therefore a well-defined feature in pipe made in a straight-through press.

The non-productive periods during the recharging of the vertical and horizontal lead presses of the present types are a serious disadvantage, so that on the grounds of economy in time we welcome the production of a continuous-extrusion machine which is capable of producing featureless lead pipe or cable sheathing.

From our experience with lead presses we would suggest that in addition to suitable temperature gradients within the machine and hence suitable heating and cooling devices, it is essential that air should not gain access to the machine and that the steel from which the machine is made should not fail at the high temperatures used. Failure of over-stressed steel in contact with lead alloys has occurred in vertical presses.

As regards the airtightness of the machine, it must be remembered that bearings and joints which are liquid-tight may not be airtight. This is particularly important as the lead moving within the machine may tend to accelerate the leakage of air at certain positions.

It is now generally recognized that lead and its alloys containing tin or antimony can penetrate into the hardened and tempered steel along the grain boundaries in the austenite, if the steel is highly stressed at raised temperatures. As soon as this inter-crystalline penetration has commenced the steel is weakened, stresses are raised at the roots of the cracks, and serious fractures may soon develop. It is therefore essential that suitable steels be selected, and that the machine be so designed that the working stresses are within the safe working range for the steel at the working temperature of the machine.

The curve (Fig. 11) showing the die temperatures obtaining on the Henley extrusion machine, if representative, indicates that the alloys can be extruded satisfactorily, and at the temperatures shown even the 0·85 % antimony alloy can be formed without producing the transverse cracks which are the result of the "hot short" property of this alloy.

Mr. E. F. Michael (*communicated*): The design of extrusion machine described by the author should effectively eliminate the various forms of weakness associated with lead sheathing extruded on the type of lead press which for many years has been regarded as standard in the cable industry. Many points arise, however, which call for comment and further elucidation from the author. For instance, on page 358 the importance of rigidity of point and die relative to one another is emphasized, and one would infer from some early remarks (page 354) that this was achieved by the provision of four supports or struts connecting the two. In view of the obstruction to the lead stream which would be offered by such supports this would appear to bé a departure from the principle of avoiding the possibility of "layering," which the author considers important even in a continuous-extrusion machine.

In connection with the precautions taken to ensure a homogeneous stream of metal, it would be interesting to learn the precise manner in which the variation of the depth of the threads on the impelling members contributes to that end.

Reference is made to a device for preventing escape of

high-pressure lead through the clearance spaces by the provision of threaded surfaces to create a back pressure as soon as any lead enters. In another design of lead-extrusion machine in which the lead is impelled by the reaction between an externally threaded rotor and an internally splined barrel the same principle is employed to prevent the escape of lead between the inner surface of the rotor and the tubular point-holder. In this case, however, the principle is more fully utilized. Not only does it prevent the escape, but, as the clearance space is fed from the opposite end with molten lead from the furnace, it actually adds to the volume of lead extruded. Fig. A shows the essential features of this machine.

The automatic tubular lead-melting furnace described on page 364 should fulfil all that is claimed for it and work with the minimum of attention, provided that the entry of foreign matter associated with pigs of lead can be avoided. In practice the surface of commercial pig lead frequently contains embedded impurities, and the set surface, especially at the edges, is likely to contain a considerable amount of dross. There will surely be a tendency to accumulate non-lead material in the upper portion of the melting chamber, and it would be interesting to know how this is dealt with.

Finally, in a machine and layout so designed as to reduce manual operation to a minimum it is rather surprising to find that such a simple process as loading pigs of lead involves lifting them one at a time by hand. The advantages to be gained by crane loading would appear to be so great as to justify a modification of this feature of the design.

[The author's reply to this discussion will be found on page 375.]

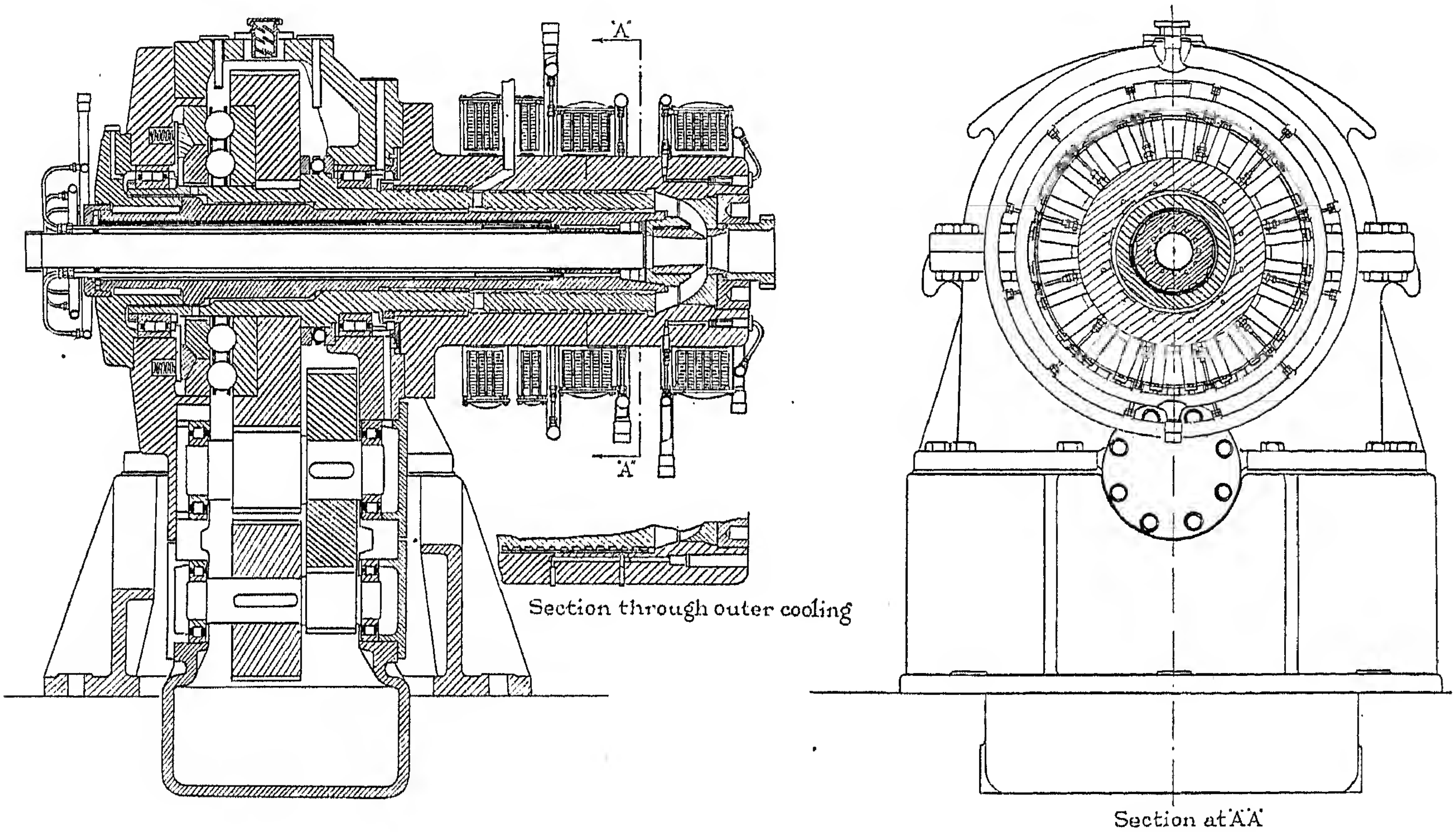


Fig. A

NORTH MIDLAND CENTRE, AT LEEDS, 8TH DECEMBER, 1936

Mr. R. M. Longman: Some years ago a case came to my notice of a fault in a cable which had been laid about 30 years. There may have been a number of incipient faults in the lead due to oxidization splits or to pinholes, which ultimately led to failures, but thanks to the barbarous methods of switching in faulty cables once, twice, or three times, all traces of the incipient or original fault had been destroyed. Possibly now by the adoption of routine d.c. testing such defects may be detected before they develop to such an extent as to destroy the evidence. Undoubtedly such faults will only be detected long after the maintenance period has expired.

The author's method of continuous extrusion is of particular value for the larger conductors and the higher-voltage cables now in use. Expansion and contraction due to loading of such cables—especially of the large single-core cables which cannot be armoured—would produce fatigue in the lead and quickly develop any manufacturing flaw.

Mr. S. R. Siviour: The two points on which the author claims advantages for his machine, namely economy of output and quality of product, are matters of great interest to cable users.

As regards economic output, it must be patent to all that the machine gives a considerable saving of time by eliminating the stoppages required with the hydraulic

press for recharging purposes, in addition to which the author claims a saving of lead required; both these factors lead one to hope that cable makers who adopt this machine will pass on at least a part of their savings to cable buyers! As regards quality of product, we know that the presence of oxide or dross in cable sheaths is detrimental and is liable to cause ultimate splitting of the sheath, with resultant entry of moisture and failure of insulation; the elimination, therefore, of the greater part—if not the whole—of the oxide and other impurities is a great gain. I am well aware that very great improvements have been made in reducing this oxide menace in modern lead pots and presses of the hydraulic type—I have seen the operation and results of the particular method referred to by the author and it is certainly a very great improvement—but one still has the disadvantage of the constant stoppages, common to both vertical and horizontal presses, and in the case of the vertical type of press the added risk of an imperfect weld. The question might well be asked: Has the past experience of cables made with the older process been such as to condemn the hydraulic press? Judged from a record of faults which can be definitely assigned to split sheaths, many engineers might be inclined to say "No." Figures relating to Continental and American systems have indicated a considerable amount of trouble due to split lead, but there is no complete record in this country. In the case of many cable faults all evidence as to the cause is destroyed, and I feel pretty certain—by reason of other symptoms—that in some of these cases a local defect in the sheath was the primary cause of breakdown.

I have always felt that with the hydraulic press there is the possibility during the period of stoppage for recharging—whilst the insulated core is in the die block—of the heat from the latter driving the oil away from the length affected and leaving a more or less dry spot. The continuous process of the new machine entirely removes this risk.

Referring to Figs. 10 and 11, the average temperature with the hydraulic press appears to be about 350° F., whereas with the extrusion machine the figure is about 395° F. I believe high temperature affects the grain size —the higher the temperature the larger the grain—but I believe the smaller grain size is preferred as in this case distortion is more general. Has the apparently higher temperature in the latter case any significance in this respect?

With regard to the machine itself, in view of the enormous pressure in the forming chamber I should like to know what special provision has been made to deal with the thrust, and what materials are used. Another interesting feature of the machine is the ingenious arrangement for continuous feeding of the tubular lead furnace. I should like the author to say whether there is any measurable amount of oxide formation with this lead furnace—there is bound to be a little, I suppose—and what method is adopted for removing this.

Mr. G. Ezard: The paper is of special interest for it clearly indicates the close attention being paid by manufacturers to the all-important question of providing a mechanically sound sheath, and it is reassuring to users to note that manufacturers do appreciate the cost of cable failures and their disturbing effects on consumers.

Quite naturally, the author prefers the continuous-extrusion type of machine; but there are modern cable factories equipped with the vertical ram type of machines which are turning out miles of satisfactorily lead-sheathed cables every week. To one who has seen such presses in operation it is interesting to read of the disadvantages which they possess, but I do not read of any advantages they may have over the screw type. The great objection to the vertical ram type of press is undoubtedly the period when the cable is at rest in the dies during the recharging of the lead containers, and one is apt to question the condition of the dielectric after its exposure to such heat. There surely must be some considerable migration, and possibly disintegration, of the oil, and I should be glad of further information on this point. The author refers to certain melting pots having a capacity of 2 tons. I know of one machine where the pot has a capacity of 1 ton and where it is possible to recharge the press in 2 minutes. The cable makers claim, however, that no damage is done to the cable during the period of standing.

There is approximately 1 900 lb. of lead in a 250-yard drum length of 3-core 0·15-sq. in. 11-kV cable made to B.S.S. No. 480, Table 8. In this case, therefore, the manufacturers should be able so to arrange the amount of metal in the container that no stop marks occur. For cables of the 460-volt grade I think similar arrangements would apply up to 250 yards of 5-core 0·25-sq. in.

The curve in Fig. 10 shows a drop in temperature at the dies of approximately 80 deg. F. during the "recharge" period. I have recollections of motor-generators which are used with suitable thermostatic control to heat the dies, but I do not know the temperature range which applies to such machines. Would the author please state whether his curve applies to gas-heated or to electrically-heated dies?

It is claimed that the "Judge" press overcomes many of the disadvantages of the vertical ram type; but one would imagine that a large slug of lead around cable which is stationary, until the lead is sufficiently cool to permit its taking a permanent shape under the influence of the ram, would cause very serious disintegration of the dielectric.

Turning to the heading "Quality of Product" (page 372), it is of interest to remember that when B.S.S. No. 480 was adopted in 1933 the practice ("unless otherwise specified") of immersing lead-sheathed cables in water for a period of 24 hours prior to voltage testing was considered unnecessary. Whether this action was taken owing to the known improvement in cable-sheathing technique, or because of any useful purpose not being claimed, I am unaware; but perhaps the author would inform us whether any faults in the lead sheath have been discovered by the voltage test after such cables have been immersed in water for 24 hours.

Plates 1 and 2 show to a marked degree the segregation of the lead and its oxides, and it would be of interest to know how the author prepares such samples for examination; as lead, owing to its softness, cannot be treated in a similar manner to steel or iron.

Mr. J. R. Kennedy: With the cutting-out of the drossing door and the adoption of the new type of lead-filling arrangement, has it been found necessary for the

buying section to check over more carefully the quality of the incoming pigs? The drossing door in the old type of machine gave one at any rate a second chance of getting rid of any impurities in the lead as supplied to the factory.

Secondly, with the modern 132-kV and 66-kV oil-filled cables especially, the cost of joints is very large indeed. Furthermore, the risk of a breakdown at the joint is greater than that of a breakdown on the cable itself. I should be interested to learn whether the adoption of this machine will enable longer drum lengths to be employed, thus cutting down the large cost of joints and reducing the possible chance of weakness in any definite run of cable.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON AND LEEDS

Dr. P. Dunsheath (*in reply*): In any discussion of a new development which may be claimed to be revolutionary, in that it provides new methods or plant likely to supersede methods and plant already in wide general use, it is natural to find lusty champions of the *status quo*. The hydraulic lead press has for many decades held an extremely important position in the lead pipe and cable industry, and any attempt to assail that position is bound to be strenuously resisted. The defence of the hydraulic press has been roundly undertaken by Mr. Scott, who says that I would advise cable makers to replace their presses by lead-extrusion machines immediately. This is not my recommendation at all, for the simple reason that not only would such a course be impracticable but it would be absurdly uneconomical. Here is a new device for producing lead cable-sheaths which possesses obvious and demonstrable advantages. As the industry expands and as old lead presses must be replaced, for various reasons, new plant will be required. What is definitely recommended is that when such occasions arise the claims of continuous lead extrusion should be considered before money is spent in installing reciprocating hydraulic presses. Mr. Scott poses four questions, but they are really irrelevant because even if the least favourable of the possible replies were given the question at issue would remain unaffected. Supposing, as Mr. Scott claims, that there are other causes of failures in cable sheaths besides those influenced by the adoption of the continuous lead-extrusion machine, and accepting his statement that only 5–10 % of sheath troubles can be eliminated in this way, then surely that is no reason for declining the advantage of this new device, particularly if this advantage can be secured at no extra cost of plant and carries with it the many other advantages referred to in the paper.

I am glad to see that, in concluding his remarks, Mr. Scott really agrees with Mr. Hunter as to the considerable probability of producing better cable sheaths by the continuous extrusion process, and this addition to his previous acceptance of economic superiority considerably strengthens the case for the proposals.

Other speakers have referred to the prevalence of faults caused in lead sheaths by existing manufacturing practice. Mr. Barralet, for instance, states that while British Post Office experience shows a reduction in number of cases, the German returns indicate that in that country failures due to split lead constitute a serious problem. Mr. Allcock also thinks I have painted too gloomy a picture of the technical demerits of modern cable sheaths, and I agree with all that he says about the improvements which have been effected during the past few years. I have in fact referred on page 355, under (3) Improvements in Hydraulic Press Practice, to the methods he describes. These are also referred to by Messrs. Hill and Beckinsale.

Mr. Allcock is a cable maker, and I am bound, therefore, to set against his remarks those of Mr. McClelland and Mr. Siviour, two users with wide experience, who consider the entire elimination of exposure and oxidation, and intermittent operation made possible by the continuous extrusion process, to be a great advantage. The remarks of Mr. Gray, too, are of considerable interest in this connection. Mr. Gray, who is a leading authority in the allied industry of lead-pipe manufacture, considers that the presence of oxide accounts for 50 % of pipe failures.

Several speakers have referred to the employment of the continuous lead-extrusion machine for alloys. Mr. Hunter goes so far as to warn users against the machine on this account, but I am afraid his information in regard to alloy difficulties is not very up-to-date. The type of machine described in the paper has demonstrated over a number of years past its ability to extrude all the various alloys employed in cable making. When the paper was read in London I exhibited a number of sample cable sheaths which had been produced on the Henley continuous extrusion machine. Their compositions included the following:—

Pure lead: 2 % tin; 0·85 % antimony; 1·75 % antimony; 0·4 % tin, 0·25 % cadmium; 0·5 % antimony, 0·25 % cadmium.

It will be seen that, in addition to normal standard cable alloys, the machine has shown its ability to deal with others which are much more difficult to extrude. One particular machine is engaged continuously on the extrusion of a 2 % tin alloy with no indication whatever that this metal is ever likely to produce difficulties, and has, up to the present, sheathed satisfactorily half-a-million yards of cable. The ability of the machine to deal with alloys, as pointed out by Messrs. Hill and Beckinsale, is entirely a question of design and choice of steels employed in its construction, combined with the correct die temperature. Failures of overstressed steel in contact with hot lead and alloys may be a very serious problem in this type of engineering plant, but it is a point which has received careful consideration in the development of the machine described.

Reference has been made by several speakers to the importance of die temperature control, and I entirely agree with Mr. Gray that there is a definite connection between the temperature at which an alloy pipe is coiled and the quality of the resulting product. Mr. Gray emphasizes the difficulty of maintaining a uniform die temperature in a reciprocating type of extrusion device, and this view appears to be generally supported. The

reply to Dr. Radley's query in connection with Figs. 10 and 11 is that the data were quoted to show the difference in variation of temperature with time; there is no significance in the actual height of the curves. It would have been equally relevant to have quoted, in Fig. 11, results from a continuous extrusion machine running at 350° F., the approximate average of the curve in Fig. 10, or at 300° F., the minimum of Fig. 10. In either case the variation with time would have been negligible, as indicated, and the machine can be run at these temperatures if required. These remarks also deal with one of Mr. Siviour's comments and on Mr. Ezard's query on the same question I would point out that the fluctuation of die temperature in a lead press during the extrusion of a charge is largely due to the effect of the metal arriving at and passing through the die. Very efficient control, whether by gas or electric heating, of the die temperature itself would be necessary to eliminate this effect in an intermittently operating machine.

As would be expected from his long study of the metallurgical problems affecting cable sheaths, Mr. Barralet has made a valuable contribution to the discussion. He has examined a section of cable sheath from a continuous extrusion machine fitted with bridge supports, and has found sharp radial lines, showing that an impression had been left on the structure of the lead, although he concludes they do not constitute a defect because they do not result in a deterioration of the bursting strength. I have made a detailed study of this phenomenon during the past year or so, and although I am unable to give Mr. Barralet a complete theory to account for my observations, I am able to throw some light on the problem.

It now seems to be quite clear that if the lead stream is split and flows over a steel part before joining up again, something takes place in the structure which can be brought to light by subsequent deep etching. It cannot be emphasized too strongly that the effect is entirely different from previously discussed incipient fissures with oxide present. In the former well-known defect the line of incipient cleavage consisted of a "mush" of small non-crystalline particles, dross, etc., and was frequently backed up on each side by sandwiches of crystals and mush, evidently on their way to form the defect. In all cases the non-uniformity was brought to light by the usual etching methods, and the crystal structure was definitely broken at the boundary line. My recent observations show that with this new phenomenon the "line" brought out by deep etching is not a boundary between two separate crystal systems, but actually passes through the crystals themselves and, moreover, passes continuously from one crystal to the next. The distinction is shown in the two photomicrographs, Figs. B and C (see Plate 1, facing page 354).

One would be inclined to advance the view that the deep etching line of Fig. C cannot be due to oxide as it is produced on a machine from which all oxide is excluded. It might easily happen, however, that a small quantity of oxide, disseminated throughout the mass of lead probably in solution, could be segregated at the dividing barrier and produce the effect, and yet be so small in quantity as to permit the free re-crystallization of the metal as in Fig. C, or there may be a type of slip band introduced on the lines suggested by Mr. Beckinsale in another connection. Another possible explanation is that in rolling and rubbing over the dividing steel surface a segregation of the very small quantities of impurities takes place and that the line therefore indicates a slight difference in alloy which still permits complete crystallization, but under certain conditions of etching produces the line depression by differential solubility through electrolytic local action.

The above remarks are necessarily tentative and theoretical, but the important practical point affecting the successful operation of the continuous extrusion machine described in the paper is that by a modification in design the offending bridge-piece has now been eliminated and a sample of pipe from an up-to-date machine will be found to be free from the feature discussed. This statement also replies to Mr. Barralet's other question on the effect of running the machine at too low a temperature. At the other extreme, if the temperature is maintained too high there is no time for adequate re-crystallization, and the operator would quickly get a warning from the appearance of the pipe. In practice, indicating thermometers on the control panel give a warning of the position long before harm can result.

No systematic investigation has so far been carried out on the prevention of segregation of alloy components due to the use of the continuous extrusion machine, but it does seem reasonable, as suggested by Mr. Barralet, that there is less chance of this occurring than when large masses of metal are solidified as in the hydraulic press.

The last point raised by the same speaker—the question of making exceptionally thin lead sheaths—is important. Some of the thinnest sheaths ever extruded have been made on the machine described in the paper, and the explanation is to be found in the uniformity of thickness made possible by the method. The results of a recent examination of pipe from a continuous machine compared with similar pipe from a hydraulic lead press are enlightening and are shown in Fig. D.

Several speakers have referred to the stop mark produced on a hydraulic press (see, for example, Fig. 5). Mr. Allcock's experience is that they do not matter, but Dr. Radley does not quite agree unless the temperature of the die is very carefully watched. Other speakers, including Mr. Ezard, have expressed some misgiving in regard to the effect of allowing a cable to stand in a press during recharging, and probably the real answer is that while the factor of safety of cables is sufficient to cover any local deterioration that may take place, and we need not be unduly alarmed, the continuous process does possess some advantage on this score.

A number of points of detail affecting the operation of the machine have been raised and call for brief comment. Regarding Mr. Allcock's query on stopping and starting, it is possible to stop the machine for some minutes and start off again with no perceptible change in sheath dimensions. It is also very easy to run the machine at a crawl. Further, the emptying of the impelling members is such a simple matter that for a long stoppage it is the usual practice to run out the lead after closing the valve connecting the lead pot.

The normal time for changing dies and getting correct dimensions, naturally depends to some extent on the skill

of the operator, but it is quite a usual thing to shut down on one size, trepan the lead, replace the die and point, and run with true lead on the new size in about 20 minutes. After the new die and point have been inserted, the obtaining of correct tube dimensions is only a question of 2 or 3 minutes.

Mr. Purse queries the use of gas for heating. Personally I favour electric heating, but the position to-day is that where electric heating is required the makers of a machine of this kind are in the hands of outside experts, whereas gas-heating of lead extrusion devices is a well-established practice. The adoption of electric heat has therefore been slow, but as an alternative to gas it is already being demanded and supplied.

On a point raised by Messrs. Hill and Beckinsale I can say that access of air to the inside of the machine has been carefully guarded against, and no single case of trouble from this cause has been encountered during 6 or 7 years' experience with various models.

The question of the bridge support for the point-holder, raised by Mr. Michael, has already been disposed of in replying to another speaker. The detailed study of layering and design of machine has now resulted in complete elimination of this feature; the lead enters the forming chamber with no obstructing barriers whatever. On the question of thread depth raised by the same speaker, to deal with this point adequately would occupy more space than I am allowed and I would take the liberty, therefore, of referring Mr. Michael to the specifications of various patents granted to myself, and others pending, where the question is fully described. This same speaker furnishes a sectional view of the machine referred to in the footnote on page 353. Here, again, much could be said as to the relative merits of the original Henley continuous lead-extrusion machine designed by myself, and this later proposal, but the space allotted for replying to the discussion does not permit. Both Mr. Michael and Mr. Kennedy raise the question of drossing facilities in the tubular lead-melting furnace shown in Fig. 13. The complete emptying of the furnace at the valve M is a simple operation, and the interior is at once opened up for thorough cleaning whenever required. Crane loading of pigs does not, in my opinion, justify the cumbrous plant layout involved, and the pig magazine and elevator described in the paper appear to give a reasonable compromise between a manual system on the one hand, and a completely automatic system on the other. Mr. Kennedy also asks whether the adoption of this machine will enable longer drum-lengths to be employed. Actually the length of cable made is usually settled by size and weight of drum, so that the answer, generally speaking, must be in the negative.

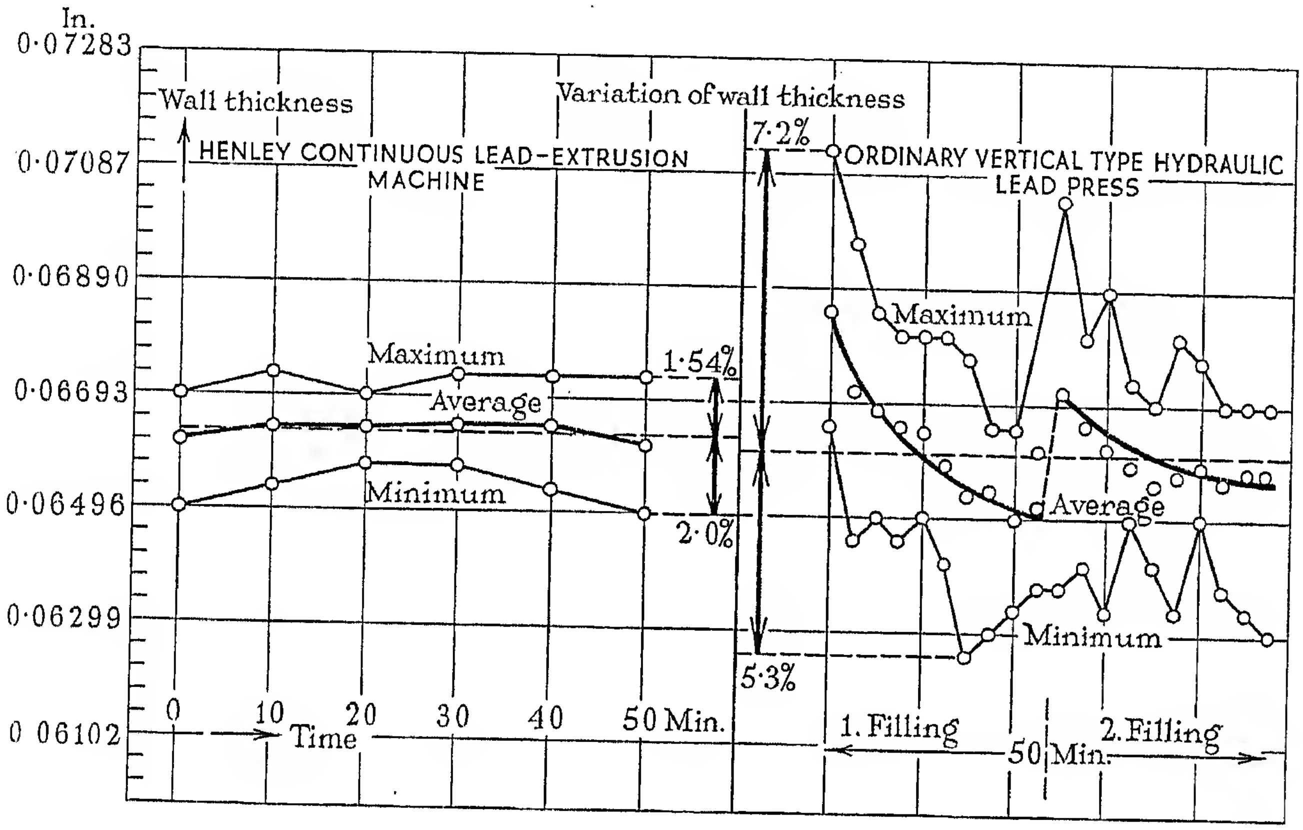


Fig. D.—Uniformity in cable-sheath dimensions. Typical improvement over hydraulic-press methods. Dia. over lead 1·08 in.

Although Mr. Ezard's question about water immersion for test is rather outside the scope of the present paper it can be disposed of very quickly. There is a good deal of uncertainty about the entrance of water through a defective lead sheath on an impregnated paper cable during the short period of a factory test. Obviously it depends on the size of the hole in the lead. With a cable having an appreciable thickness of dielectric it is almost certain that the water will not penetrate the dielectric sufficiently to show up during the test, and even with a low-tension cable the chances are that a defective sheath would never be found by this method. I would refer Mr. Ezard to various metallurgical publications for detailed methods of preparation of the lead section for microscopic examination. The technique is now well established.

THE PROPERTIES OF A DIELECTRIC CONTAINING SEMI-CONDUCTING PARTICLES OF VARIOUS SHAPES*

By R. W. SILLARS, B.A.

(*Paper first received* 21*st July and in final form* 28*th November*, 1936.)

SUMMARY

It is pointed out that, although dielectric losses in certain materials are frequently attributed to the presence of particles of conducting impurity, any discussion as to the type and magnitude of loss produced by a given quantity and disposition of impurity is often extremely vague or entirely lacking. A description is given of some experiments with a suspension of water droplets in wax, the results of which did not agree with the predictions of Wagner's theory except when the suspension was kept at a temperature near to the melting point of the wax.

The behaviour of a model inhomogeneous material containing spheroidal particles is investigated analytically and it is concluded that a minute amount of conducting impurity in the form of fine needles could produce a serious loss at low frequencies, although the effect of the same quantity of impurity in spherical form would be negligible.

CONTENTS

LIST OF SYMBOLS†

a = length of unique semi-axis of spheroid.
b = length of common semi-axis of spheroid.
h = constant.
δ = loss angle.
ϵ = field strength.
κ = dielectric constant (may be complex).
κ' = real component of κ.
κ'' = imaginary component of κ.
κ_∞ = dielectric constant when $\omega = \infty$.
f = frequency, in cycles per sec.
$N \equiv qn^2\kappa_1'/[\kappa_1'(n-1)+\kappa_2']$
$K \equiv 9q\kappa_1'/(2\kappa_1'+\kappa_2')$
l_a, l_b = coefficients depending on ratio of axes of spheroid.

LIST OF SYMBOLS—*continued*

$n = 4\pi/l_a$.
q = fractional volume of conducting material present.
σ = a.c. conductivity of inhomogeneous matrix.
σ_2 = conductivity of semi-conducting medium.
T, τ = time-constants.
P = power loss per unit volume.
ω = angular frequency, in radians per sec.
Subscript 1 indicates continuous insulating medium.
Subscript 2 indicates disperse semi-conducting medium.

(1) INTRODUCTION AND PRELIMINARY DISCUSSION

(a) Statement of the Problem

For over half a century it has been recognized that the peculiarities in the dielectric behaviour of solid substances are likely, in many cases, to be due to the presence within them of regions of higher conductivity than the general bulk of the material. A good insulator having some particles of semi-conducting material embedded in it would usually show a higher apparent conductivity in an alternating field than in a steady field: in general its conductivity would be a function of frequency. On the application of a steady field it would also exhibit the phenomena of "after-effect" or "absorption."

Maxwell, employing the simplest possible model of an inhomogeneous dielectric, consisting of plane sheets of materials having different ratios of conductivity to dielectric constant, showed that this model provides a plausible qualitative explanation of the sort of phenomenon observed with actual dielectrics.

This result, sufficient to show that the so-called anomalous behaviour of dielectrics might be explained in terms of the ordinary laws of conduction, is not enough for the engineer who wants to determine the cause of loss in a particular dielectric, so that it may be eliminated and a more satisfactory material obtained. A variety of possible alternatives is presented, including dipole rotation, ionic conduction limited by space charge, and ionization in gaseous voids; and of these at least two different hypotheses usually appear capable of giving a rough explanation of the same observed phenomena.

The problem is not simplified by the fact that the behaviour of a given material under varying conditions of frequency, temperature, electric stress, etc., usually suggests that more than one type of mechanism must be invoked to explain this behaviour in all its aspects.

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† Excluding certain symbols used in Appendix 1.

For example, it is likely that dipole rotation is an important cause of energy loss in some materials at radio frequencies, but the d.c. after-effects in the same materials are presumably to be ascribed to some manifestation of ionic conduction. The type of phenomenon which may be attributed to a given mechanism is often only vaguely delineated, partly because precise information is lacking about the physical data involved, partly owing to incomplete knowledge of the properties of the hypothetical mechanism itself.

When examining the possibilities of such a mechanism it is necessary to analyse the behaviour of a model having an assigned structure, imitating as closely as possible the physical conditions of the real material, and then see how nearly this model simulates the behaviour of the real material it is supposed to represent. This paper attempts to enlarge the analysis of the model which consists of an inhomogeneous dielectric. The conducting regions in a real inhomogeneous dielectric are of unknown, presumably irregular, shape, so that it is impossible to make our model accurately represent the real material; but it is desirable that it should take account, in some way, of the large variety of possible shapes which the inhomogeneities might assume.

(b) Wagner's Model

Wagner's analysis* assumed that the conducting particles were spheres, sparsely distributed throughout a material of comparatively low dielectric loss. His results for the a.c. characteristics of such a matrix are given in equations (1), (2), and (3).†

The real component of the dielectric constant (i.e. corresponding to the current in phase quadrature with the applied voltage) is given by

$$\kappa' = \kappa_\infty\left(1 + \frac{K}{1 + \omega^2 T^2}\right) \quad . \quad . \quad . \quad . \quad . \quad (1)$$

In this equation

$$\kappa_\infty \equiv \kappa_1'\left[1 + \frac{3q(\kappa_2' - \kappa_1')}{2\kappa_1' + \kappa_2'}\right]$$

$$K \equiv \frac{9q\kappa_1'}{2\kappa_1' + \kappa_2'}$$

$$T \equiv \frac{2\kappa_1' + \kappa_2'}{4\pi\sigma_2}$$

where κ_1' and κ_2' are the dielectric constants of the continuous (insulating) and disperse (conducting) media respectively, σ_2 is the conductivity of the latter (in c.g.s. electrostatic units), q is the small quantity of conducting material expressed as a fraction by volume, and ω is the angular frequency of the alternating current.

The form of equation (1) shows that κ_∞ is in fact the limiting value of κ', when ω approaches infinity. For small values of q, which are the only cases of practical interest, κ_∞ differs little from κ_1'.

The imaginary component of dielectric constant (corresponding to the current in phase with the applied voltage) is given by

$$\kappa'' = \kappa_\infty \frac{K\omega T}{1 + \omega^2 T^2} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If δ is the "loss angle" of the matrix, we have

$$\tan\delta = \frac{\kappa''}{\kappa'} = \frac{K\omega T}{1 + K + \omega^2 T^2} \quad . \quad . \quad . \quad (3)$$

It is also usual to define a quantity σ called the "apparent a.c. conductivity," such that

$$\sigma = \frac{\kappa''\omega}{4\pi}$$

The variation of κ'' with ω and T is very similar to the corresponding variation of tan δ, and though the latter is the quantity usually determined experimentally the former is more convenient for analytical discussion.

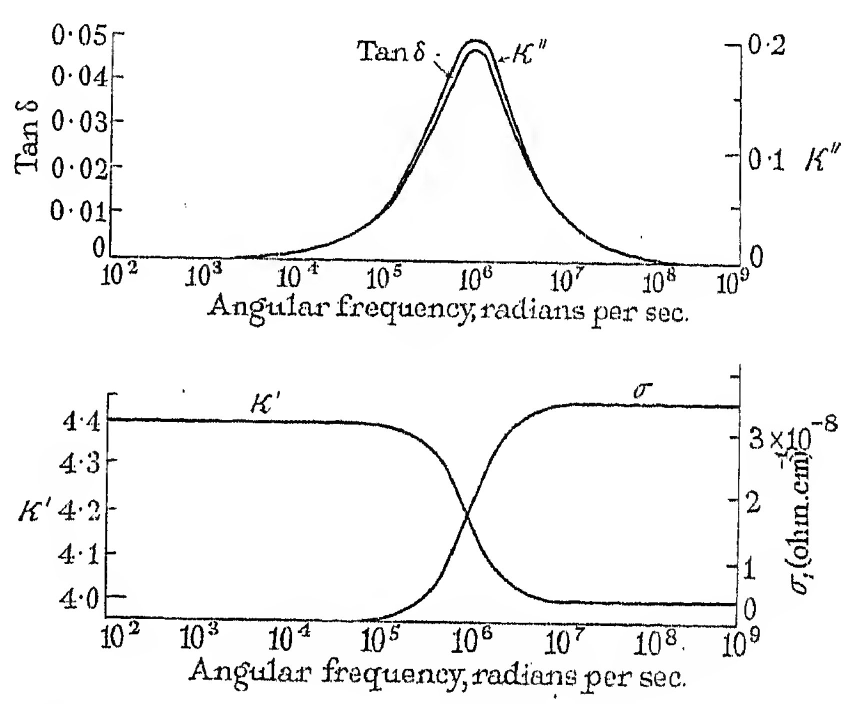


Fig. 1.—Properties of simple Wagner model dielectric, with $\kappa_1' = \kappa_2' = 4$, $\sigma_2 = 9\cdot54 \times 10^5$ e.s.u. $= 1\cdot06 \times 10^{-6}$ (ohm. cm.)$^{-1}$, and $q = 0\cdot033$.

Fig. 1 shows these various quantities plotted against log (frequency) for a particular hypothetical case where $K = 0\cdot1$ and $T = 10^{-6}$ sec. Reference to equations (1) to (3) will show that both κ'' and the change in κ' are directly proportional to K, which itself is directly proportional to q, the fraction of conducting medium present. On the other hand, T is independent of q but involves σ_2, the conductivity of the disperse medium. Thus it follows that a change in the value of σ_2, q being constant, moves the curves of Fig. 1 bodily along the frequency axis without change of form or height.

But experience shows that if the observed values of tan δ for a real dielectric are plotted against log (frequency), the resulting curve seldom has a striking resemblance to that of Fig. 1. This is not surprising, for it is likely that the conducting particles will not all have the same conductivity, and we might expect the curves for an actual dielectric to be the resultant of a whole series of curves of the type shown in Fig. 1.

* See Reference (1).

† Here, and in Section (3) of this paper, it is assumed that the continuous medium is a perfect insulator. The inclusion of a finite conductivity for the continuous medium considerably complicates the equations while adding little to the general conclusions. Wagner's equations with this conductivity included are given in Reference (1)(*b*).

Suppose the fraction dq of conducting material having conductivity lying between σ_2 and $(\sigma_2 + d\sigma_2)$ is a function of σ_2 such that

$$dq = f(\sigma_2)d\sigma_2$$

Then $f(\sigma_2)$ represents the distribution of the particles classified according to conductivity. The corresponding contributions to K can be expressed as a function of T. Thus we may write, say,

$$dK = F(T)dT$$

and Hopkinson's superposition principle can be used to sum all the contributions and obtain the relations*

$$\kappa' = \kappa_\infty \left[1 + \int_0^\infty F(T)\frac{dT}{1 + \omega^2 T^2} \right] \quad . \quad . \quad (4)$$

$$\kappa'' = \kappa_\infty \int_0^\infty F(T)\frac{\omega T dT}{1 + \omega^2 T^2} \quad . \quad . \quad . \quad (5)$$

corresponding to expressions (1) and (2). From (4) and (5), tan δ and σ are to be derived as before.

If the form of $f(\sigma_2)$ is assumed, the corresponding variation of κ', κ'', etc., with ω can be determined. Conversely, it is presumably possible to find a form for $F(T)$ and hence for $f(\sigma_2)$ which will give curves of κ', κ'', etc., agreeing with any given set of experimental results.

Wagner† supposed the logarithms of the conductivities of the particles to be distributed about a central value according to the Gaussian error function (the distribution, for example, of bullets about the centre of a target). We then have

$$F(T) = \frac{kb'}{\sqrt{\pi}}\frac{1}{T}e^{-\left(b' \log \frac{T}{T_0}\right)^2}$$

Here T_0 is the central time-constant, k is proportional to the quantity q of conducting material, and b' is the measure of the degree of scattering. Making b' large is equivalent to assuming that all the particles have conductivities very near to the central value; b' small implies that they are spread over a wide range. By suitable adjustment of this constant the curves of κ'' and tan δ can be flattened out, with corresponding diminution in the slopes of the curves of κ' and σ, and a nearer resemblance to the sort of curve found experimentally is shown.

(c) Influence of Details of Model

It is essential to remember that the forms of equations (1), (2), and (3) are not peculiar to Wagner's theory. Thus Debye's theory of dipole rotation in liquids, which appears to be roughly applicable to some solids, gives relations which are formally identical. Indeed, any mechanism in which the effects decay exponentially with time must give relations of this sort. The case of a layer of semi-conducting material in series with a layer of perfectly insulating material (Maxwell's case) is represented if we put

$$K = \frac{q\kappa_1'}{(1 + q)\kappa_2'}$$

$$T = \frac{q(\kappa_1' + \kappa_2') + \kappa_2'}{(1 + q)4\pi\sigma_2}$$

$$\kappa_\infty = (1 + 2q)\frac{\kappa_1'\kappa_2'}{q(\kappa_1' + \kappa_2') + \kappa_2'}$$

in equations (1), (2), and (3); q becoming now the ratio of the thickness of the conducting layer to the whole thickness.

In Fig. 2, curve (a) represents the variation of κ'' with ω for such a combination of two layers, curve (b)

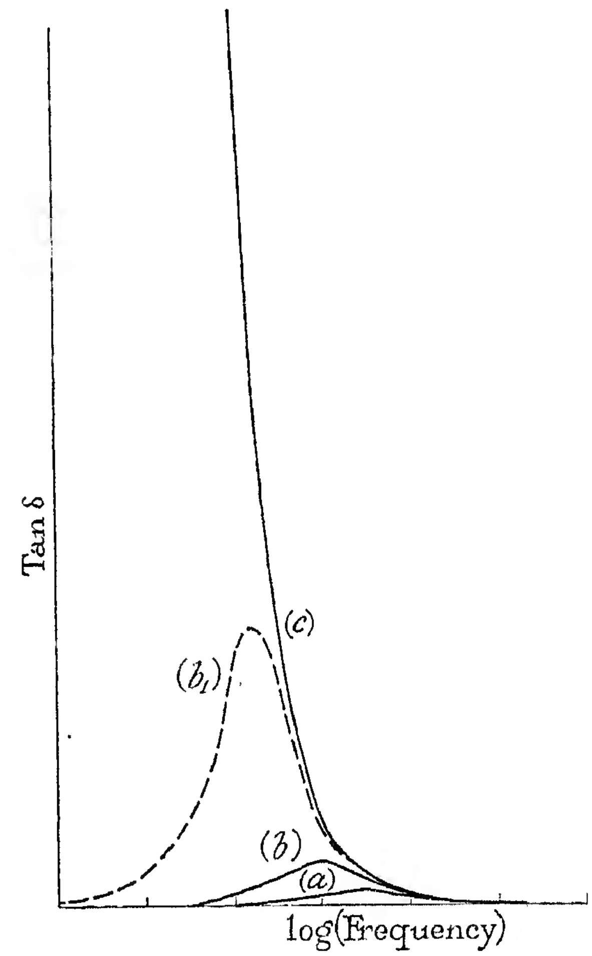


Fig. 2.—" Loss angle " caused by a given quantity of conducting material in the form of (a) sheet, (b) spheres, (c) cylinders.

the corresponding relation when the same quantity of conducting material is dispersed as spheres throughout the insulating material. There is a considerable difference in the respective heights and positions of the maxima of the two cases, a circumstance which leads one to inquire what characteristics will appear with still other dispositions of the conducting material. The only other simple case is that of a uniform sheet of insulating material with uniform cylinders of semi-conducting material extending from one face to the other, with their axes perpendicular to the faces. In this case κ'' is proportional to $1/\omega$, as illustrated by curve (c) (Fig. 2), which refers to the same fraction of conducting material as do curves (a) and (b). These three curves together suggest that if the semi-conducting material were distributed as elongated particles parallel to the field, some

* See Reference (2).

† *Ibid.*, 2(b) or 2(c).

such curve as (b_1) might result, so that it might be possible for a given quantity to produce a far greater loss than is predicted by Wagner's treatment, rising to a maximum at a much lower frequency.

A fairly simple but rather limited case is that of a plane slab of thickness $(d + s)$ containing uniform cylinders of semi-conducting material extending from one face almost to the other (Fig. 3). The distance s of the upper ends of the cylinders from the upper face is supposed to be small compared with the cross-section of the tubes, which in turn is small compared with the total area of the slab. The ratio of the total cross-

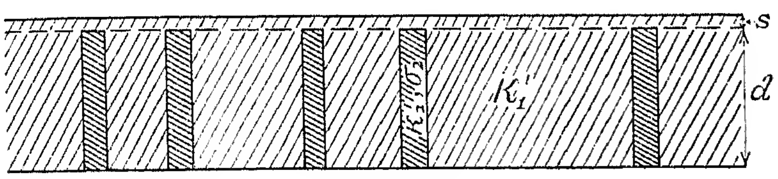


Fig. 3

section of the cylinders to the total area of the slab is then q.

The impedance Z between electrodes of area A in contact with the opposite faces is that of the circuit of Fig. 4, where

$$C_1 = \frac{\kappa_1' A}{4\pi d} \text{ approx.} \qquad C_1' = \frac{q\kappa_1' A}{4\pi s}$$

$$C_2 = \frac{q\kappa_2' A}{4\pi d} \qquad R_2 = \frac{d}{qA\sigma_2}$$

For this circuit we have

$$\frac{1}{Z} = \frac{R_2\omega^2 C_1'^2 + j\omega\left\{C_1' + C_1 + R_2\omega^2\left[C_1'^2(C_2 + C_1) + C_1'(2C_1C_2 + C_2^2) + C_1C_2^2\right]\right\}}{R_2^2\omega^2(C_2 + C_1')^2 + 1}$$

If we regard this combination of insulator and conducting cylinders as a single material having an effective conductivity σ, we can say

$$\frac{A\sigma}{d} = \frac{R_2^2\omega^2 C_1'^2}{R_2^2\omega^2(C_2 + C_1')^2 + 1}$$
$$= \frac{R_2^2\omega^2 C_1'^2}{R_2^2\omega^2 C_1'^2 + 1}$$

approximately, since $s << d$ and therefore $C_1' >> C_2$.

Hence $$\kappa'' = \frac{4\pi\sigma}{\omega} = \frac{4\pi d}{A}\cdot\frac{R_2^2\omega C_1'^2}{R_2^2\omega^2 C_1'^2 + 1}$$
$$= \frac{qd\kappa_1'}{s}\cdot\frac{\omega T'}{1 + \omega^2 T'^2}$$

where $$T' = \frac{d\kappa_1'}{4\pi s\sigma}$$

The maximum value of κ'' occurs when $\omega T' = 1$, and is given by

$$\kappa''_{max.} = \frac{qd\kappa_1'}{2s}$$

From these last two expressions it appears that if s becomes small, not only $\kappa''_{max.}$ but also T will become very large, corresponding to a higher maximum in a region of lower frequency. Although this supports the suggestion made in discussing Fig. 2, this case is a very special one, and the conclusions may not hold for particles whose lengths are not comparable with the thickness of the dielectric.

The behaviour in an alternating field of an insulator containing long filaments of partially-conducting material has frequently been discussed in connection with moisture-absorbing dielectrics,* usually in terms of a somewhat arbitrary equivalent circuit such as that of Fig. 4. No definite conclusion is reached in such discussions as to the magnitude of the effects produced by a given quantity of conducting material. Only Wagner's treatment gives a definite answer on this point, and Wagner himself considered this answer to be substantially correct whatever the shape of the inhomogeneities.† Against this opinion, however, we have not only the considerations set out above, but some evidence that Wagner's equations do not satisfactorily explain experimental observations. For example, if in equation (3) we put $\kappa_2' = 82$ (the value for water), $\kappa_1' = 3$ (say), and $q = 0{\cdot}05$, we get

$$\tan\delta = \frac{0{\cdot}0154\omega T}{1{\cdot}015 + \omega^2 T^2}$$

the maximum value of which is $0{\cdot}0077$. It is well known that 5 per cent of moisture in a dielectric often produces a much greater power factor than this.

As a more precise example, some measurements made by Wagner‡ on paper may be quoted. In a paper of dielectric constant (dry) $1{\cdot}14$, $8{\cdot}6$ per cent of moisture produced an increase of $\tan\delta$ ranging from $0{\cdot}116$ at $\omega = 3\,000$ to $0{\cdot}046$ at $\omega = 40\,000$, while 4 per cent of moisture produced an increase ranging from $0{\cdot}0057$ to

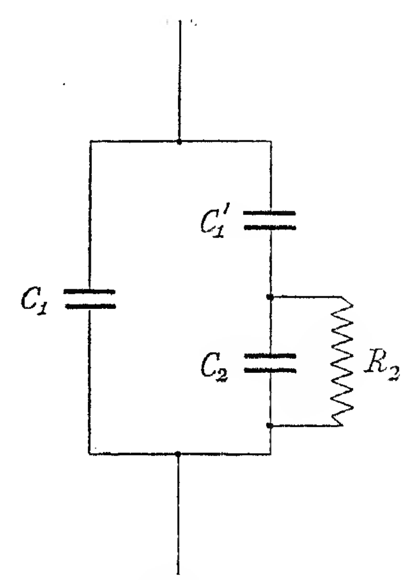


Fig. 4

$0{\cdot}0035$ between the same frequencies. The maximum values from equation (3) are about $0{\cdot}005$ in the first case, and $0{\cdot}0024$ in the second. The experimental curves show every appearance of rising to still higher values

* See Reference (3). † *Ibid.*, (4). ‡ *Ibid.*, (5).

at lower frequencies, although the measured d.c. conductivity does not approach the conductivities corresponding to these power factors. Further, in order to explain the fact that the value of tan δ only falls by a factor of about ½ while the frequency changes by a factor of 10, it is necessary, on Wagner's theory, to assume a considerable scattering of the conductivities of the particles. This will still further decrease the maximum calculated power factor, and still further increase the discrepancy. Similar results were obtained by Lubben,* who found an increase of tan δ ranging from 0·0029 at 3 000 cycles per sec. to 0·0020 at 30 000 cycles per sec. with 4 per cent moisture, and from 0·043 to 0·015 with 7·5 per cent moisture. Again the curves had not reached a maximum but were rising with decreasing frequency.

It is worth while noting that in order to explain the common appearance of appreciable losses at frequencies of the order of 1 000 cycles per sec., it is necessary on Wagner's theory to assume that the water has a conductivity as low as that of the purest water obtainable. A slight trace of electrolyte should be sufficient to lower the value of T and so shift the curve of tan δ so far to the high-frequency region that no appreciable loss would be found at audio and power frequencies. It has often been observed, on the contrary, that the presence of electrolytes in insulating materials greatly increases these losses when moisture is present, without producing a d.c. conductivity nearly great enough to account for this increase.

It may be objected that the conducting regions in moisture-absorbing dielectrics cannot be regarded as droplets of water having the same properties as water in bulk. It is possible that water may be adsorbed in layers on the inner surfaces of the pores of the material, rather than sucked in by those pores as by capillary tubes. Recent research on the nature and properties of ionic layers at the boundary of two media has also led to various speculations by Böning, Murphy and Lowry, and others, as to the behaviour of fine channels of electrolyte under the influence of electric fields, and the bearing of this on problems of dielectric loss. Since it is generally assumed that such channels are long and thin, it is desirable to examine the effects which might be produced by conducting pores whose lengths, though not necessarily comparable with the thickness of the material, are yet much greater than their diameters, so that they cannot be regarded, even approximately, as spheres.

Before the analytical consideration of this question is pursued any further, some experiments will be described which first drew the author's attention to the need of such consideration.

(2) EXPERIMENTS WITH AN ARTIFICIAL INHOMOGENEOUS DIELECTRIC

The experiments here described were aimed at making observations on the variation of tan δ with frequency on a material as nearly approaching Wagner's conception as possible.

The values of tan δ at radio frequencies were deduced from the measured width of the resonance curve of a simple LCR circuit, the condenser of which contained the material under investigation. For measuring values of tan δ less than 0·08 the capacitance was kept constant and the frequency of the oscillator supplying the exciting electromotive force was varied.* For values of tan δ greater than 0·08 the necessary frequency-change inevitably involved a change in the output of the generator, and it was found more convenient to vary the capacitance, by means of a parallel condenser, and maintain the frequency constant. The latter method involves the possibility of error due to inductance of the leads to the parallel condenser. It was estimated that this error was never more than 2 per cent, an estimate confirmed by the agreement found with the frequency distuning method at neighbouring frequencies.

The audio-frequency measurements were made with a capacitance bridge provided with a Wagner earth, the source being a valve oscillator and the detector an amplifier and headphones.

The condenser containing the material to be measured consisted of a shallow chromium-plated brass dish 12½ in. in diameter, serving as a containing vessel and as the lower electrode, fitted with a glass cover having a central screwed brass bush to carry the vertical stem of the upper electrode. A similar condenser with air as dielectric was placed alongside this for comparison by substitution.†

In order to imitate Wagner's model, it was decided to suspend droplets of water of suitable conductivity in molten paraffin wax, and to allow the wax to solidify so that the drops were frozen into position. The power factor of the wax employed was known to be less than 0·0003 at all the frequencies concerned.

The initial difficulty of inducing the water to break up into droplets fine enough to remain in suspension while the wax solidified, was overcome, after some experiments, by the addition of about 1 per cent of calcium palmitate to the wax.‡

The loss, if any, that the small quantity of calcium palmitate might bring about due to dipole rotation, or (conceivably) ionic conduction in the wax, was expected to be small or negligible; this was subsequently confirmed.§

It was not found practicable to adjust closely the conductivity of the water in suspension, for although this might be brought to the desired value before mixing with the wax, it seemed that the calcium palmitate, or some trace of electrolyte associated with it, or with the wax, produced an increase of conductivity which could not be accurately predicted. It has already been noted that this would merely move the curve of tan δ to a higher range of frequencies, without affecting its height or shape.

The frequency distuning method is best suited to the measurement of power factors of the order of 0·01. Accordingly 25 g of water were shaken up with 300 g of wax, representing approximately 6·7 per cent of water by volume. A conductivity of 5×10^{-5} (ohm. cm.)$^{-1}$ was aimed at for the water. The dielec-

* See Reference (6).

* See Reference (7).
† *Ibid.*, (8).
‡ The author is grateful to Mr. F. C. Frank, of the Oxford Engineering Laboratory, for suggesting this emulsifier. The quantity used was perhaps unnecessarily large, since a considerable proportion of it remained as a coarse suspension.
§ See page 384.

tric constant of the wax was known to be $2 \cdot 18$, so that according to equation (3) a maximum value of $\tan \delta$ equal to $0 \cdot 0076$ should appear in the neighbourhood of $1 \cdot 04 \times 10^6$ cycles per sec. (corresponding to a wavelength of 286 m).

The measurements were started a few days after the suspension had been made, and proceeded systematically from the highest to the lowest frequency, occupying about a week. The values of $\tan \delta$ obtained are plotted

reflecting galvanometer—was 36 megohms, corresponding to a conductivity of about $1 \cdot 9 \times 10^{-11}$ (ohm. cm.)$^{-1}$. Current/time measurements showed a slow decrease of current of the usual type to which no particular significance could be attached.

Curve C of Fig. 5 shows the observed capacitance of the test condenser plotted against the logarithm of frequency. The dotted curve represents the power factor attributable to a leakage resistance of 36 megohms,

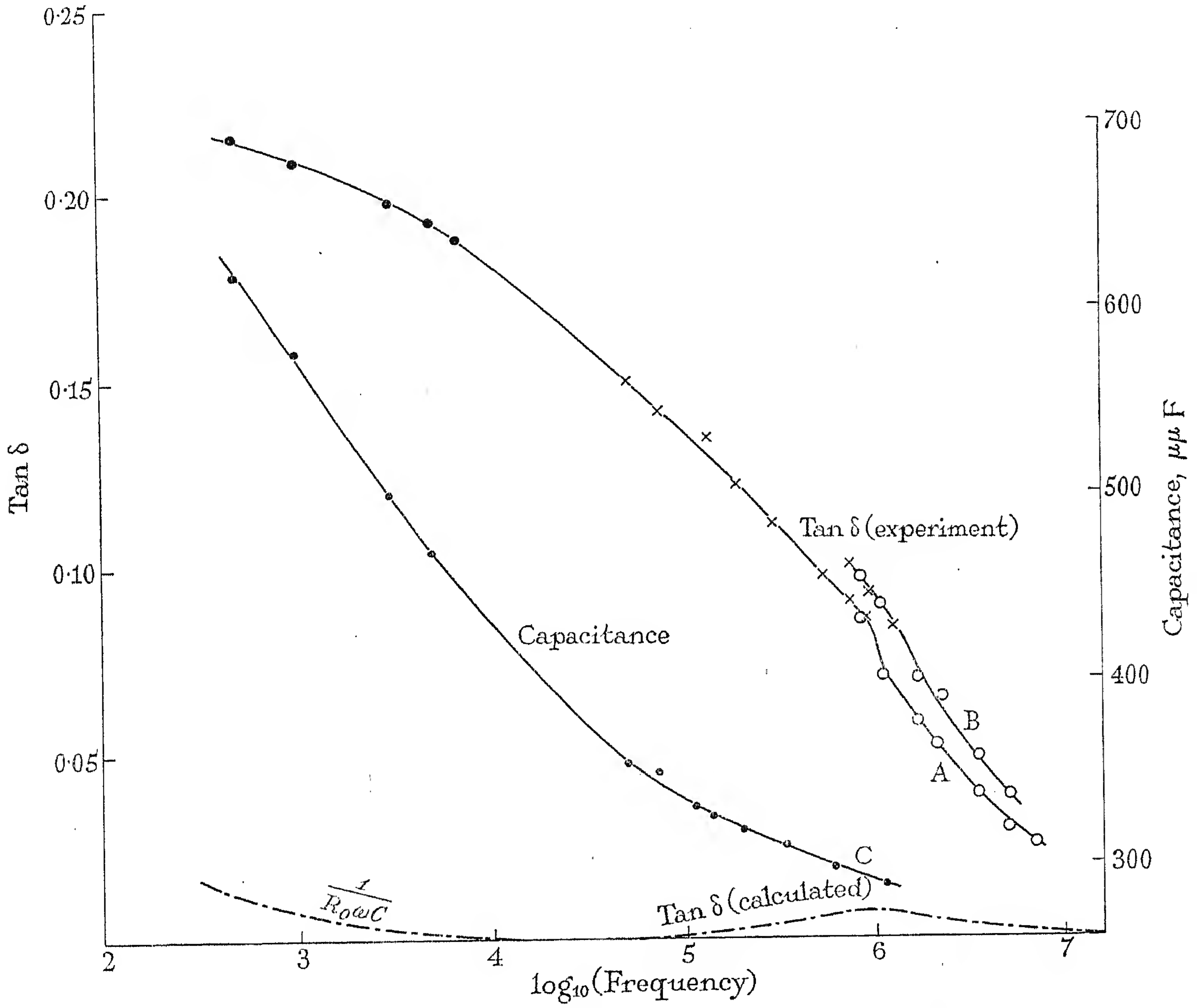


Fig. 5.—Results obtained with first suspension.

o Frequency distuning measurements. × Capacitance distuning measurements. • Bridge measurements.

against log (frequency) in Fig. 5, curve A. After these observations had been completed some measurements in the high-frequency range were repeated; these are recorded by curve B, which shows that the values of $\tan \delta$ were consistently increasing with age. The temperature of the suspension for all the readings was 15° C. All the measurements were made with an electric stress not greater than 400 volts per cm., and it was observed that the values of $\tan \delta$ were independent of voltage within the accuracy of observation (about 1 per cent).

The d.c. resistance of the condenser containing the suspension—measured with a 10-volt battery and calculated from the frequency and the appropriate capacitance given by curve C.

The chain line in the same figure shows the curve of $\tan \delta$ to be expected from equation (3), calculated from the quantity of water present, and its conductivity as measured before mixing with the water. Contamination of the water with electrolyte could only move this curve as a whole towards the right of the diagram, so that the formula is quite incapable of explaining either the form or the magnitude of the experimental curve A. On the other hand, curve A is the type of result which ordinary experience would lead one to expect from a material containing 6 or 7 per cent of water.

At the conclusion of these measurements the solid wax was broken up and examined. The wax was originally poured into the condenser in two layers, the first of which had partially solidified before the second was added. Examination of the broken wax showed that the droplets had tended to concentrate near the bottom of each layer, indicating that some settling had taken place during solidification of the wax. The large majority of the droplets, however, were well away from the bottom electrode; indeed, only a trace of water, less than 1 per cent of the original 25 cm.^{3}, was found on the bottom of the condenser. By dipping a broken section of the wax in aniline blue the edges of cavities in the plane of the section could be demonstrated; a microphotograph of such a section is shown in Fig. 6. The division between the two layers can be seen as a horizontal line across the centre of the photograph, and the cavities appear as somewhat irregular closed curves of dark stain. What appears to be a long horizontal cavity on the left of the photograph is due to an accidental pool of dye lying on the wax. It will be seen that the droplets, though not perfectly spherical, are not so different from spheres that one would expect as complete a departure from the predictions of Wagner's formula as is shown by Fig. 5.

The broken wax was finally melted, the water allowed to settle, and the wax poured off and maintained at 100° C. under reduced pressure for 2 hours to remove all traces of moisture. On pouring the wax back into the condenser, allowing to cool and repeating the power-factor measurements, no loss could be detected at any frequency, the minimum power factor which could have been detected being 0·0001 in the radio-frequency and 0·0005 in the audio-frequency measurements. Since the calcium palmitate was still present, and was again effective in bringing about the suspension of water when next added, the possibility of loss connected with it seems to be eliminated.

It appeared from calculations which are set out in Section (3) of this paper that the experimental results might be explained by the existence of fine fissures in the wax which, although containing a comparatively small quantity of water, could produce a considerable loss, extending to the low-frequency range. The method used in making the water-wax suspension is likely to produce such fissures, for in cooling down from its melting point to room temperature the wax contracts considerably more than the water over the same range of temperature, so that one might expect minute cracks to be initiated at the surfaces of the water-containing cavities, and the water to be forced into these.

To test this hypothesis it was decided to hold a similar suspension at a temperature a few degrees below its solidifying point. It was thought that the electrical properties should approximate more closely to those predicted by Wagner's equations, because fissures would be unlikely to form to so great an extent in the slightly plastic wax which had not greatly contracted.

A suspension, containing about 6 per cent of water by volume, was made by mixing 15 g of water with 200 g of the wax used for the previous experiments. The suspension was poured into the condenser, which was maintained at 52·5° C. (about 9 deg. C. below the solidifying point of the wax) until the conclusion of the measurements. As before, readings were taken in order of decreasing frequencies, one of the high-frequency points being repeated at the end of the audio-frequency measurements. Curve A of Fig. 7 shows the results of these measurements, the point Y being the repeated reading. It is seen that the energy loss appears chiefly in the high-frequency region, and that over a considerable range of frequencies this mixture containing 6 per cent of water had a power factor less than 0·002. The chain curve in Fig. 7 shows values of tan δ calculated from equation (3). It appears that the water had acquired a much greater conductivity than was anticipated, displacing the maximum of tan δ so far to the right that it was only just within the range of frequencies employed. This was presumably due to contamination with electrolyte, either accidentally during manipulation or by a trace of acidic oxidation product in the wax. As only a fraction of a milligram of electrolyte would be sufficient to produce this displacement, such contamination is quite probable, and it was not thought worth while to make another suspension. The fact that the repeated point Y falls about 10 per cent below the previous measurement at the same frequency, taken some hours earlier, is probably due to a slow drift of the curve towards the right, as a result of absorption of traces of electrolyte from the wax during the course of the experiment. At a temperature near to its melting point it is likely that an appreciable amount of diffusion can take place in the wax.

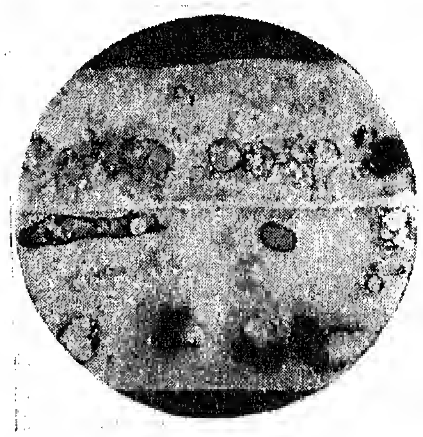


Fig. 6.—Section of water-wax suspension (magnification = 10).

The difference between the heights of the calculated and experimental curves will be considered in Section (4).

The d.c. resistance of the test condenser was greater than 1 000 megohms [conductivity less than about 6×10^{-13} (ohm. cm.)$^{-1}$] throughout the experiment. The enclosure required to maintain the condenser at 52·5° C. made capacitance measurements impracticable.

Curve B of Fig. 7 shows the results obtained from the same mixture, 4 days after it had been allowed to cool down to room temperature. It is of the same general form as curve A of Fig. 5, though the losses are smaller. The condenser in the second experiment was contained in a water-bath of large heat capacity, which delayed the cooling considerably. That the values of tan δ are larger in the first experiment tends to confirm the

hypothesis that the departure from Wagner's formulae is due to fissures in the wax, since rapid cooling would be expected to favour the formation of fissures.

Alternating-field problems in a system of partially conducting dielectrics can be solved by the methods of electrostatics, if the idea of a complex dielectric constant

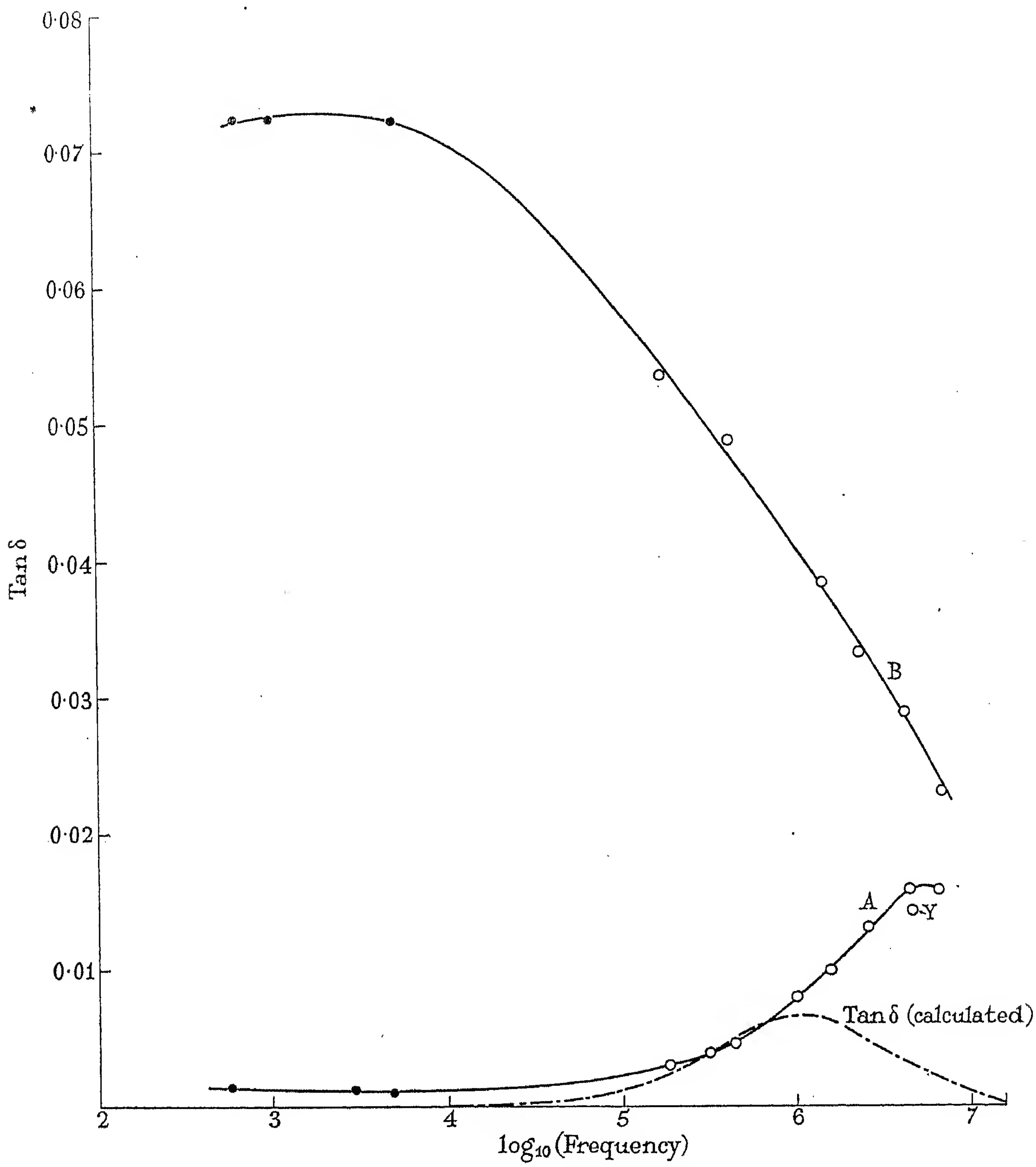


Fig. 7.—Results obtained with second suspension.

○ Frequency disturbing measurements.
● Bridge measurements.

Curve A. 9 deg. C. below solidifying point.
Curve B. Room temperature.

(3) EXTENSION OF WAGNER'S MODEL TO SPHEROIDAL PARTICLES

It has been suggested that elongated particles of partially-conducting material embedded in an insulator may produce effects seriously different from those predicted by equations (1), (2), and (3). The non-spherical shape which is most easily amenable to analytical treatment is the spheroid, the form of which may vary from that of a flattened lens to that of an elongated needle, a range sufficient to indicate whether the suggestions contained in Section (1) are on the right lines.

is used, in the manner suggested by Wagner.* Consider first the boundary conditions at the surface between two imperfectly insulating materials of dielectric constants κ_1' and κ_2' and conductivities σ_1 and σ_2. Let the corresponding normal components of the alternating field be given by

$$\epsilon_1 = {}_0\epsilon_1 e^{j\omega t}$$
$$\epsilon_2 = {}_0\epsilon_2 e^{j\omega t}$$

where ${}_0\epsilon_1$ and ${}_0\epsilon_2$ may be complex quantities.

* See Reference (1).

The net surface charge density brought by conduction is

$$\int(\epsilon_1\sigma_1 - \epsilon_2\sigma_2)dt$$

$$= \int({}_0\epsilon_1\sigma_1 - {}_0\epsilon_2\sigma_2)e^{j\omega t}dt$$

$$= \frac{1}{j\omega}(\epsilon_1\sigma_1 - \epsilon_2\sigma_2)$$

By Gauss's theorem,

$$\epsilon_1\kappa_1' - \epsilon_2\kappa_2' = -\frac{4\pi}{j\omega}(\epsilon_1\sigma_1 - \epsilon_2\sigma_2)$$

Putting $4\pi\sigma_1/\omega = \kappa_1''$ and $4\pi\sigma_2/\omega = \kappa_2''$, we get

$$\epsilon_1(\kappa_1' - j\kappa_1'') = \epsilon_2(\kappa_2' - j\kappa_2'')$$

or $$\epsilon_1\kappa_1 = \epsilon_2\kappa_2$$

which is formally identical with the boundary condition for the normal component in the electrostatic case, but κ_1 and κ_2 are now complex quantities.

Combining this with the usual condition that potential must be continuous across the boundary, it is obvious that the solution of an alternating-field problem in conducting dielectrics can be obtained by substituting complex dielectric constants in the solution of the corresponding electrostatic problem.

Consider a model inhomogeneous dielectric consisting of a continuous medium of dielectric constant κ_1', which we will take as being a perfect insulator, containing a number of very small spheroids of medium of dielectric constant κ_2' and conductivity σ_2 dispersed throughout it. We will suppose that the distance between these particles is so much greater than their size* that each may be regarded as being under the influence of a uniform alternating field ϵ, and that they are so numerous that the whole matrix can be regarded as having a mean dielectric constant given by $\kappa = \kappa' - j\kappa''$. To simplify the treatment we will first consider only spheroids having their unique axes parallel to the field ϵ.

The properties of such a matrix can be derived by considering the potential at an external point, as in Wagner's work (see Appendix 2), but since we are principally concerned with dielectric loss it is interesting to consider the question from the point of view of energy absorption.

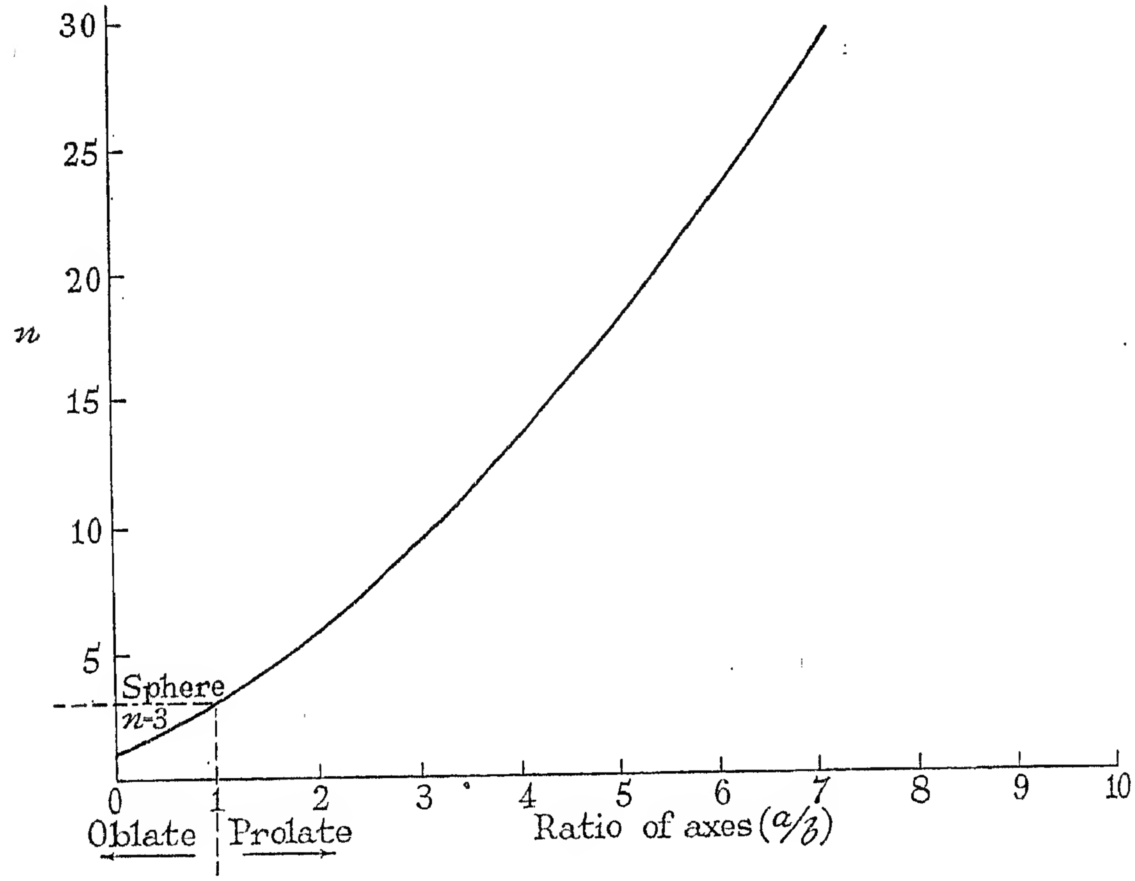


Fig. 8

The potential within one of the spheroids is given by equation (19), Appendix 1. Differentiating this, substituting $n = 4\pi/l_a$, and introducing a complex value for κ_2, the field strength within one of the spheroids is given by

$$\epsilon_2 = \epsilon\frac{n\kappa_1'}{(n-1)\kappa_1' + \kappa_2' - j\kappa_2''} \quad . \quad . \quad . \quad (6)$$

where $\kappa_2'' = 4\pi\sigma_2/\omega$. The coefficient n is a function of the eccentricity of the spheroid, varying from unity for a very flat oblate spheroid to infinity for a very long prolate one, and being equal to 3 for a sphere. It is calculated from l_a [equations (23) and (25), Appendix 1], and is plotted as a function of the ratio of the axes of the spheroid in Fig. 8.

* The assumption that the spheroids are very far apart does not introduce any serious error, for in any good dielectric the volume of conducting medium will not amount to more than 1 or 2 per cent of the total; moreover, the spheroidal model is only intended to represent roughly the infinite variety of shapes which the particles of an actual inhomogeneous dielectric might assume, and there would be no advantage in carrying out the calculations with greater accuracy.

It is easily shown that the mean power loss per unit volume of the conducting medium is given by

$$\tfrac{1}{2}\,|\,\epsilon_2\,|^2\sigma_2$$

or

$$\frac{|\,\epsilon_2\,|^2\kappa_2''\omega}{8\pi}$$

so that the mean power loss per unit volume of the whole matrix is

$$P = q\frac{|\,\epsilon_2\,|^2\kappa_2''\omega}{8\pi}$$

where q is the fractional volume of conducting medium present. It is assumed, for the present, that all the spheroids are of the same shape.

Since the matrix as a whole is regarded as having a mean dielectric constant $(\kappa' - j\kappa'')$, we can also write

$$P = \frac{|\,\epsilon\,|^2\kappa''\omega}{8\pi}$$

Equating the two expressions for P,

$$\kappa'' = q\kappa_2''\frac{|\,\epsilon_2\,|^2}{|\,\epsilon\,|^2}$$

$$= q\kappa_2''\frac{n^2\kappa_1'^2}{[\kappa_1'(n-1)+\kappa_2']^2+\kappa_2''^2} \text{ from equation (6)}$$

If we substitute

$$\omega\tau \equiv \frac{\kappa_1'(n-1)+\kappa_2'}{\kappa_2''}$$

or

$$\tau \equiv \frac{\kappa_1'(n-1)+\kappa_2'}{4\pi\sigma_2} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

and

$$N \equiv q\frac{n^2\kappa_1'}{\kappa_1'(n-1)+\kappa_2'} \quad . \quad . \quad . \quad . \quad (8)$$

then the expression for κ'' reduces to

$$\kappa'' = \frac{\kappa_1'N\omega\tau}{1+\omega^2\tau^2}$$

This is of the same form as equation (2), N and τ corresponding to K and T. The quantities N and τ, however, involve the coefficient n in such a way that both these quantities become large when n becomes large. This means that, if the conducting material is distributed in the form of long spheroids, the maximum loss-angle will be far greater than that predicted by equation (2) for a given proportion of the material, and will appear at a lower frequency, which is the suggestion made in discussing Fig. 2. It is now clear that a material containing conducting particles of various shapes may show a resultant curve of κ'' very different in shape and height from that of Fig. 1.

The values of κ' and $\tan\delta$ are most conveniently obtained by considering the potential due to an elementary volume of material; this is done in Appendix 2, and the equations obtained are:—

$$\kappa' = \kappa_\infty + \frac{\kappa_1'N}{1+\omega^2\tau^2} \quad . \quad . \quad . \quad . \quad (9)$$

$$\kappa'' = \frac{\kappa_1'N\omega\tau}{1+\omega^2\tau^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

(which is identical with the expression already obtained),

and

$$\tan\delta = \frac{\kappa''}{\kappa'} = \frac{N\omega\tau}{N+(1+\omega^2\tau^2)(\kappa_\infty/\kappa_1')} \quad . \quad (11)$$

where

$$\kappa_\infty = \kappa_1'\left[1 + q\frac{n(\kappa_2'-\kappa_1')}{\kappa_1'(n-1)+\kappa_2'}\right] \quad . \quad . \quad (15)$$

and N and τ have the values given by (7) and (8).

The effects of varying N, τ, and ω in (9), (10), and (11) are analogous to the corresponding changes in (1), (2), and (3), which have already been discussed.

Consider now the values of N and τ for certain particular values of n. If $n = 3$ (case of a sphere), we have

$$\tau = \frac{2\kappa_1'+\kappa_2'}{4\pi\sigma_2}$$

$$N = \frac{9q\kappa_1'}{2\kappa_1'+\kappa_2'}$$

which are identical with K and T for Wagner's model, and equations (9) to (11) are not significantly different from equations (1), (2), and (3.)* When $n = 1$ (limiting case of a very flat oblate spheroid),

$$\tau = \frac{\kappa_2'}{4\pi\sigma_2}$$

$$N = \frac{q\kappa_1'}{\kappa_2'}$$

which only differ appreciably from the expressions on page 380 for a layered dielectric if q is comparable with unity. To consider the case of n very large (infinitely long prolate spheroid), we rearrange (11) as follows:—

$$\tan\delta = \frac{\omega}{\dfrac{1}{\tau}+\left(\dfrac{1}{N\tau}+\dfrac{\omega^2\tau}{N}\right)\dfrac{\kappa_\infty}{\kappa_1'}}$$

As n approaches infinity, N and τ approach infinity and κ_∞ approaches $(\kappa_1' + q\kappa_2')$, so that

$$\tan\delta \to \frac{N}{\omega\tau[1+(q\kappa_2'/\kappa_1')]}$$

$$= q\frac{n^2\kappa_1'\times 4\pi\sigma_2}{\omega[\kappa_1'(n-1)+\kappa_2']^2[1+(q\kappa_2'/\kappa_1')]}$$

$$\to q\frac{4\pi\sigma_2}{(\kappa_1'+q\kappa_2')\omega} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11a)$$

Now $\tan\delta$ for a plane insulating slab, having conducting cylinders of total cross-section q extending from one face to the other, is given by

$$\tan\delta = q\frac{4\pi\sigma_2}{[\kappa_1'(1-q)+q\kappa_2']\omega} \quad . \quad . \quad (11b)$$

On comparison it may be seen that equations (11a) and (11b) differ only so far as $(1 - q)$ differs from unity.

To emphasize the importance of the shape of the particles, Fig. 9 has been prepared. It relates to a com-

* The differences, which are of the second order in q, arise from a slightly different approximation used by Wagner.

pound dielectric in which $\kappa_2' = \kappa_1'$ and $(\tan\delta)_{max} = 0 \cdot 01$, and shows how the fractional quantity q_r of impurity required to produce this loss varies with the ratio of the axes of the spheroids. As the elongation increases, the frequency $\omega_{max.}$ at which the maximum appears diminishes. For the particular case where $\kappa_2' = \kappa_1'$, the same curve exhibits this critical frequency in terms of that for a layer model, the appropriate scale being shown at the right of the figure.

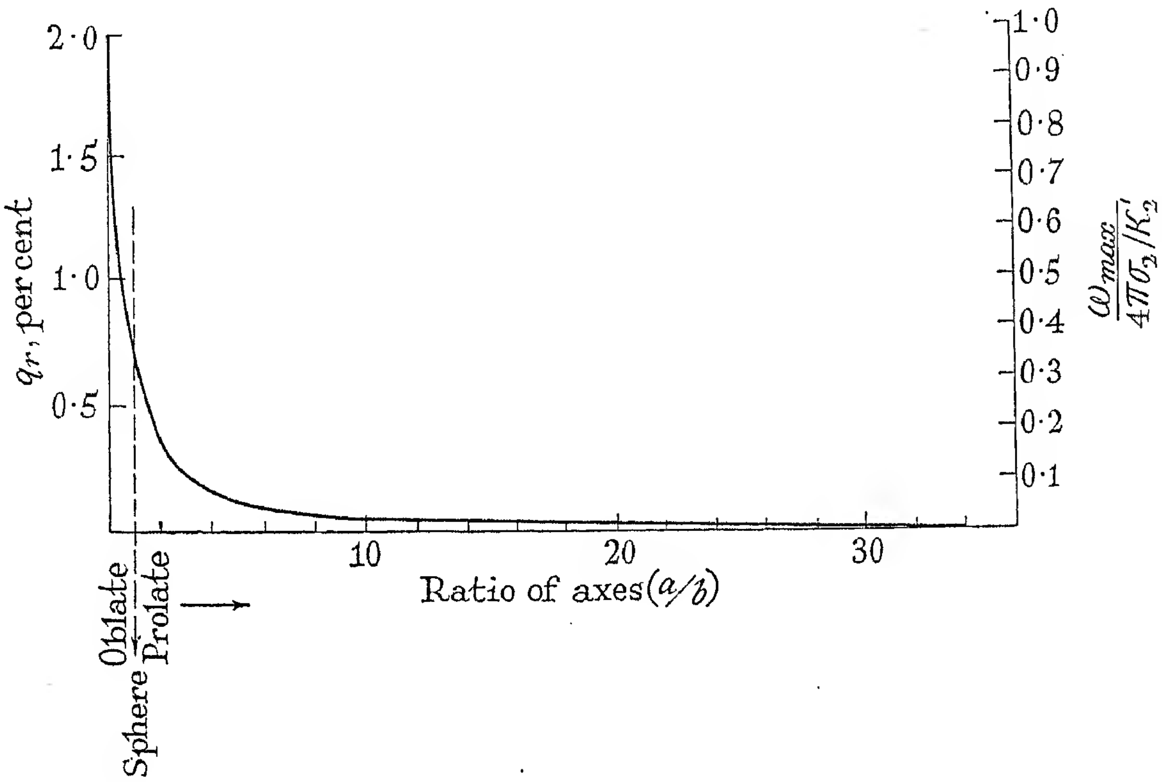


Fig. 9.—Values of q_r required to make $(\tan\delta)_{max} = 0 \cdot 01$, for a compound dielectric in which $\kappa_2' = \kappa_1'$.

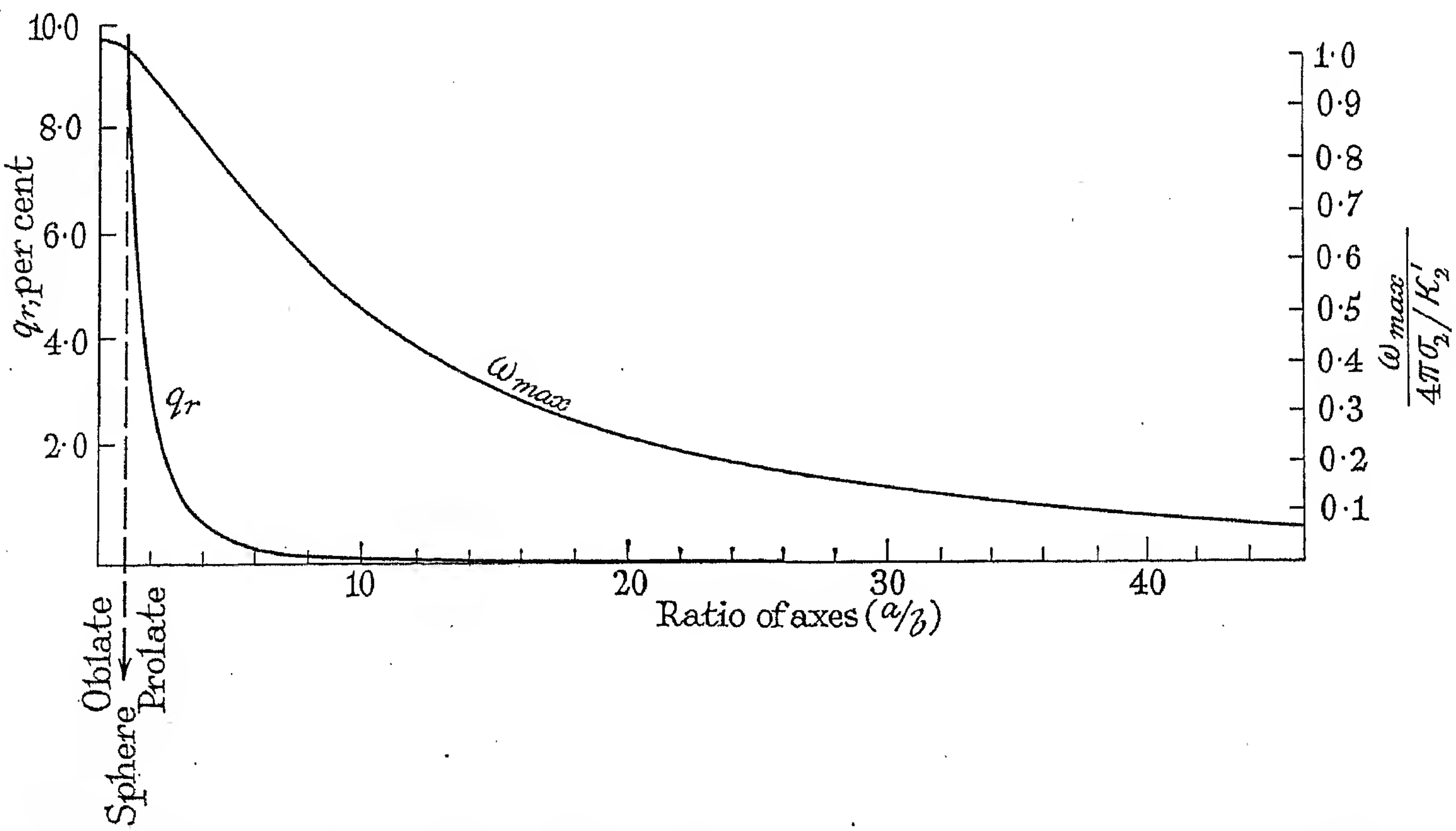


Fig. 10.—Values of q_r required to make $(\tan\delta)_{max} = 0 \cdot 01$, for a compound dielectric in which $\kappa_2' = 41\ \kappa_1'$.

Fig. 10 shows a similar curve for q_r when $\kappa_2' = 41\kappa_1'$, which is approximately the ratio relevant to water and wax. Here q_r is very large for oblate spheroids, becoming comparable with unity, so that $n = 1$ no longer gives a good approximation to the layer model. The quantity q_r falls off very rapidly with increasing elongation of the spheroids, finally approaching the same values as in Fig. 9. The critical frequency $\omega_{max.}$ at first falls very slowly in Fig. 10, but this too finally approaches the curve of Fig. 9.

For very large eccentricities the value of n for a

prolate spheroid is given [see equation (26), Appendix 1] by

$$(n)_{a/b\to\infty} = \frac{a^2}{b^2\left(\log\frac{2a}{b} - 1\right)}$$

so that N and τ may be written

$$(N)_{a/b\to\infty} = q\frac{a^2}{b^2\left(\log\frac{2a}{b} - 1\right)} \quad . \quad . \quad . \quad (12)$$

$$(\tau)_{a/b\to\infty} = \frac{\kappa_1'}{4\pi\sigma_2}\cdot\frac{a^2}{b^2\left(\log\frac{2a}{b} - 1\right)} \quad . \quad . \quad (13)$$

whatever the value of κ_2'.

There is no doubt that, given a choice of conductivity and shape, we can produce a loss of any magnitude at any frequency with as small a quantity of conducting medium as we please; again, given a conductivity, we can arrange that the maximum of tan δ shall appear at any frequency lower than $4\pi\sigma_2/\kappa_2'$, and the lower the frequency, the less quantity will be required to produce a given loss.

Before we discuss the possible applications of our model, it will be well to consider how far its details tally with what we might conceive to be the details of an actual material, and to what extent any differences in this respect are likely to affect the correctness of our conclusions.

The assumption of a spheroidal shape is a highly desirable one for analytical reasons, and it is difficult to see how else we can discuss the conducting regions which doubtless exist at inter-crystalline boundaries, in contraction voids left by the cooling of the principal insulating material and subsequently filled by less suitable material, or in the remnants of a colloidal structure left after solidification and manipulation of certain plastics.

It cannot be said that the assumption that the particles have their unique axes parallel to one another and to the field, is a very plausible representation of the supposed real dielectric, but it can be shown that it does not affect the nature of the general conclusions. The disturbing field due to a very long prolate spheroid making an angle θ with the applied field is proportional to $\cos^2\theta$, so that if we suppose such spheroids distributed with their axes in all possible directions we have over-estimated their effects by

$$\frac{2\pi\int_0^\pi \cdot \sin\theta\, d\theta}{2\pi\int_0^\pi \cos^2\theta \sin\theta\, d\theta} = 3 \text{ times}$$

(It can be shown by replacing l_a, in $n = 4\pi/l_a$, by l_b—equation (27), Appendix 1—that the effect of a long spheroid with its axis perpendicular to the main field is negligible compared with that when the long axis is parallel to the main field.) For smaller eccentricities the error is not so great, so that our results are too large by a factor of less than 3.

From Fig. 9 it is seen that for a given quantity of material the difference between the sphere case and that of a spheroid such that $a/b = 10$ is already a factor of 16 or so, while in the limit the relation of equation (12) is followed, so that a division by 3 is of little importance.

The same argument cannot be applied to oblate spheroids with their axes pointing in all possible directions, for an oblate spheroid with its unique axis perpendicular to the field will produce a much greater effect than when its unique axis is parallel to the field, as hitherto assumed. The appropriate expressions could be obtained using l_b of equation (24) instead of l_a, but the results would be similar to those already found with prolate spheroids. The only reason for introducing oblate spheroids is to show that a link exists between Maxwell's model and Wagner's. The remainder of the discussion will be confined to the prolate shape.

The assumption that the particles are very sparsely distributed is likely to lead to an under-estimate of their effects. The field near a particle falls off very rapidly with distance, so that when the particles are close they will lie in fields which are greater than has been assumed. Further, in cases where two particles lie with their ends close together, they will tend to behave as one long particle.

(4) APPLICATIONS OF THE RESULTS OF SECTION (3)

As an example of the implications of the results of Section (3), the following discussion is of interest.

Table 1

$\frac{b}{a}$	$\kappa_2' = \kappa_1'$		$\kappa_2' = 41\kappa_1'$	
	$(\tan\delta)_{max.}$	$f_{max.}$ (cycles per sec.)	$(\tan\delta)_{max.}$	$f_{max.}$ (cycles per sec.)
1	0·010	1×10^6	0·010	1×10^6
1/2	0·0048	$5{\cdot}21 \times 10^5$	0·0087	$9{\cdot}35 \times 10^5$
1/5	0·0024	$1{\cdot}68 \times 10^5$	0·0101	$7{\cdot}43 \times 10^5$
1/10	0·0016	$6{\cdot}10 \times 10^4$	0·013	$4{\cdot}81 \times 10^5$
1/50	0·0009	$4{\cdot}32 \times 10^3$	0·012	$6{\cdot}06 \times 10^4$
1/100	0·0008	$1{\cdot}29 \times 10^3$	0·011	$1{\cdot}82 \times 10^3$

Consider a dielectric containing spheres of semi-conducting material, in the manner of Wagner's model, and imagine these successively replaced by spheroids whose lengths along the field are the same as the diameter of the original sphere, but whose other two axes are progressively diminished; the volume of each spheroid is then $(b/a)^2$ of that of the original sphere. Suppose that the total quantity of the original spheres was such as to produce a maximum value for tan δ of 0·01, and that this maximum appeared at a frequency of 10^6 cycles per sec. Table 1 will then show the variation of the maximum of tan δ and the frequency at which it will appear, as b/a is diminished, for the two cases previously considered of $\kappa_2' = \kappa_1'$ and $\kappa_2' = 41\kappa_1'$.

In the first case (equal dielectric constants), tan δ only decreases to about 1/12 when the sphere's model is replaced by that of spheroids with $b/a = 1/100$,

although the volume of conducting substance has diminished to 1/10 000. The frequency at which the maximum is reached, however, has diminished to about 1/1 000 of its former value.

When $\kappa_2' = 41\kappa_1'$, $(\tan\delta)_{max.}$ for $b/a = 1/100$ is actually slightly greater than for $b/a = 1$; in this case, of course, the volume of water spheres required to produce a value of $\tan\delta$ of 0·01 is much greater than the volume of dispersed medium required to produce the same value of $\tan\delta$ in the case of $\kappa_2' = \kappa_1'$. The frequency of the maximum decreases slowly at first, but finally approaches the same values as when $\kappa_2' = \kappa_1'$.

In the limit of b/a very small, $(\tan\delta)_{max.}$ for both cases approaches the value given [see equation (26), Appendix 1] by

$$(\tan\delta)_{max.} = \frac{q}{2\left(\log\frac{2a}{b} - 1\right)}$$

The importance to low-frequency losses of minute conducting crevices is clear. It is also obvious why increasing the conductivity of the conducting particles will not, in general, banish all losses to the high-frequency region. Another finer set of cracks is brought into operation.

A compound dielectric containing conducting particles of all shapes will exhibit loss at all frequencies up to those in the neighbourhood of $1/\tau$ for spheres. The superposition principle can be used to discuss the behaviour of a model containing a quantity of conducting material distributed according to a specified law among various shapes of spheroids, just as a distribution with respect to conductivity has been discussed by Wagner (see page 380). Corresponding to equations (4) and (5), we have

$$\kappa' = \kappa_\infty + \kappa_1'\int_0^\infty F(\tau)\frac{d\tau}{1+\omega^2\tau^2}$$

$$\kappa'' = \kappa_1'\int_0^\infty F(\tau)\frac{\omega\tau d\tau}{1+\omega^2\tau^2}$$

It is of interest to see what sort of distribution will give rise to a constant value of κ'' at all frequencies. If we put

$$F(\tau) = \frac{2h}{\pi}\cdot\frac{1}{\tau}$$

where h is a constant, we have

$$\kappa'' = \kappa_1'\frac{2h}{\pi}\int_0^\infty \frac{\omega d\tau}{1+\omega^2\tau^2}$$
$$= \kappa_1' h$$

To obtain a value of κ'' equal to $\kappa_1' h$ at all frequencies, therefore, we arrange the contributions to N having time-constants lying between τ and $(\tau + d\tau)$ to be given by

$$dN = F(\tau)d\tau = \frac{2h}{\pi}\cdot\frac{d\tau}{\tau}$$

Assuming σ_2 to be the same for all particles, so that the variation of τ is due to change of n only, substitution from expressions (7) and (8) for τ and N (page 387) gives

$$dq\frac{n\kappa_1'}{(n-1)\kappa_1' + \kappa_2'} = \frac{2h}{\pi}\cdot\frac{4\pi\sigma_2}{(n-1)\kappa_1' + \kappa_2'}\cdot\frac{\kappa_1'}{4\pi\sigma_2}$$

$$dq = \frac{2h}{\pi n^2}dn \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

which is the condition for constant κ''. All values of τ from 0 to infinity cannot be covered by this relation, however, since n cannot be less than unity, and is unlikely to be less then 3. In Fig. 11 are plotted the properties of a model dielectric for which the distribution of (14) is followed from $n = 3$ to $n = \infty$, with h equal to 0·05. The same materials as were used in the hypothetical model of Fig. 1 are assumed. The total quantity of conducting medium required is given by

$$dq = \frac{2h}{\pi}\int_3^\infty \frac{dn}{n^2}$$
$$= 0{\cdot}212h$$
$$= 0{\cdot}0106 \text{ per unit volume of the mixture.}$$

A model having the same properties, but using a smaller quantity of conducting material, could be invented by giving the latter a higher conductivity, and cutting off the distribution of equation (14) at a correspondingly higher value of n.

The experiments of Section (2) of this paper find a ready explanation in terms of this kind of model. As already suggested, there is a strong probability in this case that the cooled mixture contains very fine cracks of all sorts of lengths and configurations, formed by thermal contraction and filled with water. The success of the experiment in which the wax was kept at a temperature near to its melting point is strong evidence that this is the correct explanation. The fact that the maximum of $\tan\delta$ in the latter experiment was between two and three times that predicted by Wagner's formulae may be due to the incomplete fulfilment of the conditions that the particles should be small compared with their distance from one another and from the electrodes. In view of the small loss which persists down to low frequencies, however, it seems likely to be due, in part, to the limited formation of fissures, the shorter of which will increase the magnitude of κ'' and $\tan\delta$ without greatly altering τ (cf. Fig. 10).

Confirmatory evidence of the existence of such fissures in wax is given by some experiments by Lee and Lowry* on the behaviour of materials after soaking in 3·5 per cent sodium-chloride solution. They found that samples of paraffin (melting point 51·5° C.), soaked for 6 months at room temperature, lost 0·04 to 0·11 per cent by weight on subsequent desiccation. In these experiments, of course, only pores communicating with the outer surface could take up water. They also found a.c. conductivities at 1 000 cycles per sec. corresponding to values of $\tan\delta$ from 0·002 to 0·016. These are very small compared with the results of Figs. 5 and 7, but it must be remembered that, as only the surface layers could absorb water, the layers of poor dielectric so

* See Reference (9).

produced would be in series with a considerable thickness of perfectly good wax.

As a rough summary of the above conclusions, one might say that conducting particles all of whose dimensions are of similar magnitudes are responsible for high-frequency losses, while long fine fissures, containing minute amounts of conducting material, make the chief contribution to low-frequency losses.

Since direct current may be regarded as the limiting case of low-frequency alternating current, it is interesting to compare the above conclusion with that of Evershed,* that in moisture-absorbing paper only a properties of the elements of their structures. The enormous increase of power factor over a wide range of frequencies, caused in fibrous insulation by small quantities of water, receives a plausible explanation when it is remembered that such moisture will be taken up by fine cellular channels, analogous to the long prolate spheroids of the model. As regards synthetic resins and similar materials of a colloidal nature, it has been suggested that losses in these may in part be due to conductivity of one of the components. If this be so, the shapes of the fragments of this component in the finally pressed and hardened material will have an

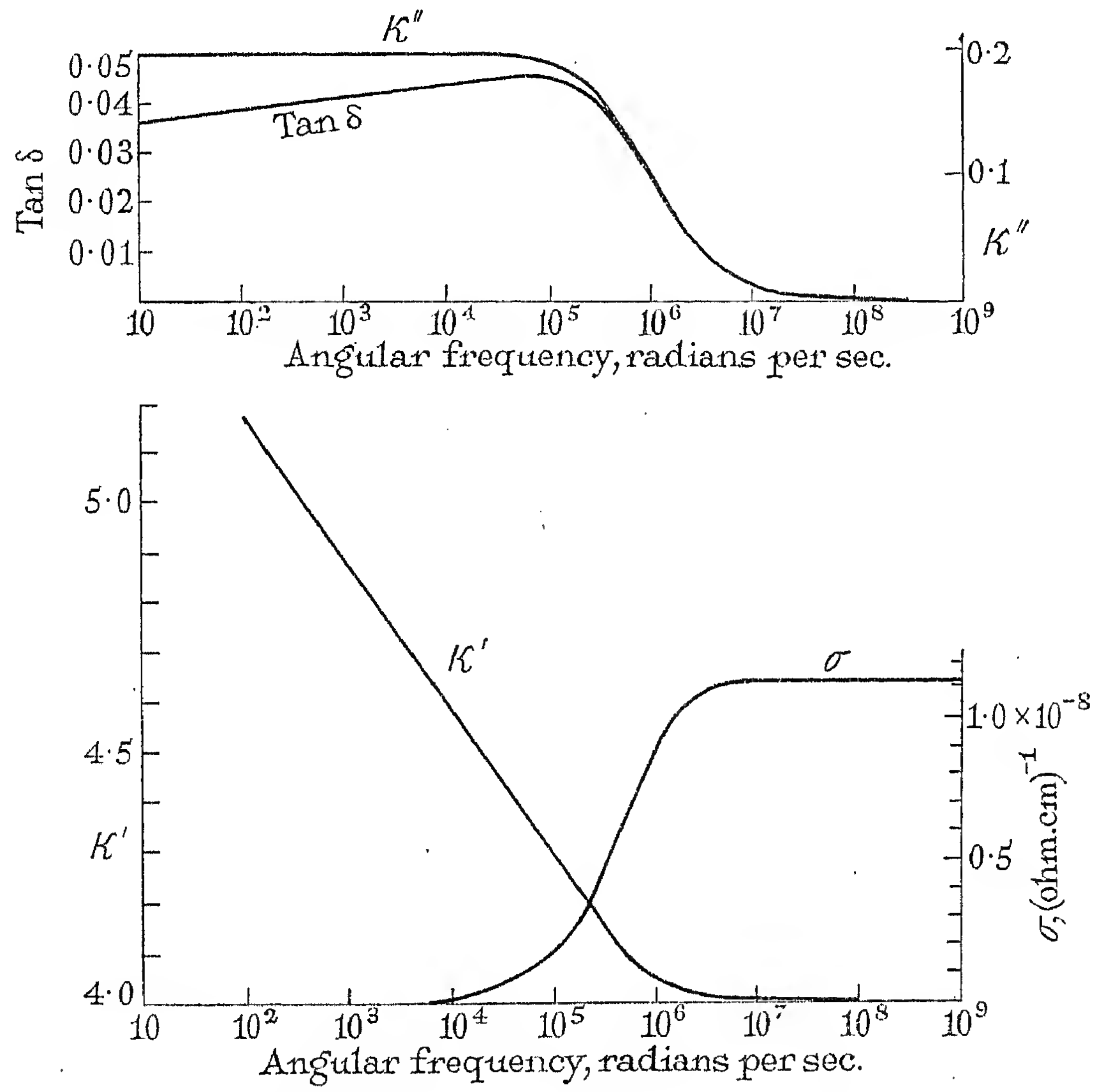


Fig. 11.—Properties of a spheroidal model dielectric with $\kappa_1' = \kappa_2' = 4$, $\sigma_2 = 9\cdot54$ e.s.u. $= 1\cdot06$ (ohm. cm.)$^{-1}$, and $dq = \dfrac{0\cdot1}{\pi} \times \dfrac{dn}{n^2}$.

minute fraction (a few parts in a million) of the total water present takes part in the d.c. conduction. The spheroidal model could, of course, be applied in explaining d.c. anomalies, the analysis being analogous to that given by Wagner.† These, however, seem so likely to be complicated by space-charge and electrolytic polarization effects that treatment in terms of a single uniform conductivity σ_2 would hardly be adequate.

It is difficult to say precisely how far the ideas outlined in this paper are important in connection with problems of loss in commercial dielectrics, owing to our uncertainty about the detailed physical structures of these materials and particularly about the electrical important influence on the losses. If they take the form of thin filaments they are likely to produce an appreciable loss at all frequencies, of the type actually found in such materials. If, on the other hand, the fragments are small and compact, approximating to spheres, a less marked loss limited, possibly, to a narrow range of frequencies should result. An accurate treatment of these two examples might be complicated by such questions as conduction at the boundaries of the different media, but the broad conclusion arrived at here is not invalidated. Much evidence has been brought forward by Smekal and others to indicate that ionic conduction in crystalline solids occurs at the boundaries of the minute "perfect crystals." A quantitative

* See Reference (10)

† *Ibid.*, (1).

discussion in terms of these theories is hardly possible, but again the configuration of the boundaries seems to be a matter of importance.

It would probably not be difficult, making suitable and for the most part plausible assumptions, to explain the losses in nearly any solid dielectric in terms of the model adopted in Section (3). This breadth of possible application, though it is commonly met with among theories relating to dielectric behaviour and is not evidence in favour of the correctness of the explanations, does imply that the discussion is of some importance, and perhaps deserves the more emphasis since it has hitherto received little, if any, attention.

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APPENDIX 1

Potential in the Neighbourhood of a Dielectric Ellipsoid placed in a Uniform Field of Force*

Preliminary Analysis.

Let the space within the ellipsoid

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}=1 \quad . \quad . \quad . \quad . \quad (16)$$

be filled with material of dielectric constant κ_2, and let the remainder of space be filled with material of dielectric constant κ_1.

Let α be the positive root of the equation

$$\frac{x^2}{a^2+u}+\frac{y^2}{b^2+u}+\frac{z^2}{c^2+u}=1 \quad . \quad . \quad (17)$$

regarded as a cubic in u, (x, y, z) being any point outside the ellipsoid given by equation (16) at which the potential is required to be known.

Put $$\frac{\sqrt{[(a^2+\alpha)(b^2+\alpha)(c^2+\alpha)]}}{2\pi abc}=\beta$$

and $$\int_\alpha^\infty \frac{d\alpha}{(a^2+\alpha)\beta}=l_a$$

Consider the following expressions for the potential at any point (x, y, z):—

$$V_1=-x\epsilon_x\left[1-\frac{\kappa_2-\kappa_1}{4\pi\kappa_1+(\kappa_2-\kappa_1)l_a}\int_\alpha^\infty\frac{d\alpha}{(a^2+\alpha)\beta}\right] \quad (18)$$

when (x, y, z) is outside the ellipsoid represented by (16), and

$$V_2=-x\epsilon_x\frac{4\pi\kappa_1}{4\pi\kappa_1+(\kappa_2-\kappa_1)l_a} \quad . \quad . \quad (19)$$

when (x, y, z) is inside the ellipsoid.

* The symbols l_a and l_b of this Appendix are identical with those in the List of Symbols (see page 378).

ϵ_x is a constant, and since at points an infinite distance from the origin α becomes infinite, the integral in equation (18) becomes zero and ϵ_x is seen to be the field strength at infinite distance from the ellipsoid. V_1 and V_2 are both solutions of Laplace's equation.*

Boundary conditions.

At points infinitely close to the surface of the ellipsoid, $u = 0$ and

$$V_1=-x\epsilon_x\left[1-\frac{\kappa_2-\kappa_1}{4\pi\kappa_1+(\kappa_2-\kappa_1)l_a}\int_0^\infty\frac{d\alpha}{(a^2+\alpha)\beta}\right]$$

$$=-x\epsilon_x\frac{4\pi\kappa_1}{4\pi\kappa_1+(\kappa_2-\kappa_1)l_a}$$

$= V_2$ at the neighbouring point just inside the ellipsoid.

Hence the potential given by V_1 and V_2 is continuous across the surface of the ellipsoid.

By differentiating equation (18),

$$\frac{\partial V_1}{\partial x}=-\epsilon_x\left[1-\frac{\kappa_2-\kappa_1}{4\pi\kappa_1+(\kappa_2-\kappa_1)l_a}\int_\alpha^\infty\frac{d\alpha}{(a^2+\alpha)\beta}\right.$$
$$\left.+x\frac{\kappa_2-\kappa_1}{4\pi\kappa_1+(\kappa_2-\kappa_1)l_a}\cdot\frac{1}{(a^2+\alpha)\beta}\cdot\frac{\partial\alpha}{\partial x}\right]$$

and, from (17),

$$\frac{2x}{a^2+\alpha}-\left[\frac{x^2}{(a^2+\alpha)^2}+\frac{y^2}{(b^2+\alpha)^2}+\frac{z^2}{(c^2+\alpha)^2}\right]\frac{\partial\alpha}{\partial x}=0$$

When the point (x, y, z) is infinitely close to the surface of the ellipsoid, this gives

$$\frac{\partial\alpha}{\partial x}=\frac{2p^2x}{a^2}$$

where $$\frac{1}{p^2}=\frac{x^2}{a^4}+\frac{y^2}{b^4}+\frac{z^2}{c^4},$$

and $\partial V_1/\partial x$ becomes

$$\left(\frac{\partial V_1}{\partial x}\right)_{surface}=-\epsilon_x\left[1-\frac{(\kappa_2-\kappa_1)l_a}{4\pi\kappa_1+(\kappa_2-\kappa_1)l_a}\right.$$
$$\left.+x\frac{\kappa_2-\kappa_1}{4\pi\kappa_1+(\kappa_2-\kappa_1)\gamma}\frac{2\pi}{a^2}\cdot\frac{2p^2x}{a^2}\right]$$
$$=-\frac{4\pi\epsilon_x}{4\pi\kappa_1+(\kappa_2-\kappa_1)l_a}\left[\kappa_1+\frac{p^2x}{a^2}(\kappa_2-\kappa_1)\frac{x}{a^2}\right]$$

Similarly,

$$\left(\frac{\partial V_1}{\partial y}\right)_{surface}=-\frac{4\pi\epsilon_x}{4\pi\kappa_1+(\kappa_2-\kappa_1)l_a}\cdot\frac{p^2x}{a^2}(\kappa_2-\kappa_1)\frac{y}{b^2}$$

and

$$\left(\frac{\partial V_1}{\partial z}\right)_{surface}=-\frac{4\pi\epsilon_x}{4\pi\kappa_1+(\kappa_2-\kappa_1)l_a}\cdot\frac{p^2x}{a^2}(\kappa_2-\kappa_1)\frac{z}{c^2}$$

The direction cosines of the normal n to the surface at the point (x, y, z) are

$$\frac{px}{a^2},\ \frac{py}{b^2},\ \text{and}\ \frac{pz}{c^2}$$

* Cf., for example, J. H. JEANS: "Electricity and Magnetism," 4th ed., p. 254.

so that

$$\frac{\partial V_1}{\partial n} = \frac{\partial V_1}{\partial x}\cdot\frac{px}{a^2} + \frac{\partial V_1}{\partial y}\cdot\frac{py}{b^2} + \frac{\partial V_1}{\partial z}\cdot\frac{pz}{c^2}$$

$$= -\frac{4\pi\epsilon_x}{4\pi\kappa_1 + (\kappa_2 - \kappa_1)l_a}\left[\kappa_1\frac{px}{a^2} + \frac{p^3x}{a^2}(\kappa_2 - \kappa_1)\left(\frac{x^2}{a^4} + \frac{y^2}{b^4} + \frac{z^2}{c^4}\right)\right]$$

$$= -\frac{4\pi\epsilon_x}{4\pi\kappa_1 + (\kappa_2 - \kappa_1)l_a}\left[\kappa_1\frac{px}{a^2} + (\kappa_2 - \kappa_1)\frac{px}{a^2}\right]$$

$$= \frac{\kappa_2}{\kappa_1}\frac{\partial V_2}{\partial x}\frac{px}{a^2}$$

$$= \frac{\kappa_2}{\kappa_1}\frac{\partial V_2}{\partial n}\left(\text{since } \frac{\partial V_2}{\partial y} = \frac{\partial V_2}{\partial z} = 0\right)$$

i.e. the normal component of electric displacement is continuous across the surface.

V_2 and V_1 therefore fulfil the necessary boundary conditions and represent the potential inside and in the neighbourhood of the ellipsoid when a field, whose undisturbed value at infinity is ϵ_x, is applied parallel to the axis of x.

General expression.

If the applied field is not parallel to the x-axis it can be resolved into components ϵ_x, ϵ_y, and ϵ_z, and the expressions for potential outside and inside the ellipsoid become

$$V_1 = -x\epsilon_x\left[1 - \frac{\kappa_2 - \kappa_1}{4\pi\kappa_1 + (\kappa_2 - \kappa_1)l_a}\int_\alpha^\infty \frac{d\alpha}{(a^2 + \alpha)\beta}\right]$$
$$- y\epsilon_y\left[1 - \frac{\kappa_2 - \kappa_1}{4\pi\kappa_1 + (\kappa_2 - \kappa_1)l_b}\int_\alpha^\infty \frac{d\alpha}{(b^2 + \alpha)\beta}\right]$$
$$- z\epsilon_z\left[1 - \frac{\kappa_2 - \kappa_1}{4\pi\kappa_1 + (\kappa_2 - \kappa_1)l_c}\int_\alpha^\infty \frac{d\alpha}{(c^2 + \alpha)\beta}\right] \quad (20)$$

and

$$V_2 = -x\epsilon_x\frac{4\pi\kappa_1}{4\pi\kappa_1 + (\kappa_2 - \kappa_1)l_a} - y\epsilon_y\frac{4\pi\kappa_1}{4\pi\kappa_1 + (\kappa_2 - \kappa_1)l_b}$$
$$- z\epsilon_z\frac{4\pi\kappa_1}{4\pi\kappa_1 + (\kappa_2 - \kappa_1)l_c} \quad . \quad (21)$$

where

$$l_b = \int_0^\infty \frac{d\alpha}{(b^2 + \alpha)\beta}$$

$$l_c = \int_0^\infty \frac{d\alpha}{(c^2 + \alpha)\beta}$$

Field at distances large compared with a, b, and c.

Expression (17) represents the ellipsoid confocal with (16) and passing through any required external point (x, y, z). If the distance of (x, y, z) from the origin is much greater than the length of any of the axes of the ellipsoid, equation (17) approaches the equation to the sphere, namely

$$\frac{x^2}{\alpha} + \frac{y^2}{\alpha} + \frac{z^2}{\alpha} = 1$$

That is, $\alpha \simeq r^2$

where r is the distance of (x, y, z) from the origin. Under these conditions

$$\int_\alpha^\infty \frac{d\alpha}{(a^2 + \alpha)\beta} \simeq \int_\alpha^\infty \frac{d\alpha}{(b^2 + \alpha)\beta} \simeq \int_\alpha^\infty \frac{d\alpha}{(c^2 + \alpha)\beta} \simeq 2\pi abc\int_\alpha^\infty \alpha^{-5/2}d\alpha$$

$$= -\frac{4\pi abc}{3}\alpha^{-3/2}$$

$$= -\frac{4\pi abc}{3}\frac{1}{r^3}$$

$$= -\frac{v}{r^3}$$

where v is the volume of the ellipsoid.

The potential at points distant from the ellipsoid is therefore given by

$$V_1 = -x\epsilon_x\left[1 - \frac{\kappa_2 - \kappa_1}{4\pi\kappa_1 + (\kappa_2 - \kappa_1)l_a}\frac{v}{r^3}\right] + \text{similar terms in } y \text{ and } z$$

Reverting for the moment to the case of $\epsilon_y = \epsilon_z = 0$, the above can be written

$$V_1 = -\epsilon_x\left[r - \frac{\kappa_2 - \kappa_1}{4\pi\kappa_1 + (\kappa_2 - \kappa_1)l_a}\frac{v}{r^2}\right]\cos\theta \quad . \quad (22)$$

where θ is the angle between the x-axis and the radius vector of the distant point. At distant points, therefore, the disturbing field due to the ellipsoid is of the same form as that due to an electric doublet, as given by the second term in equation (22).

Spheroid.

If the semi-axes b, c, of the ellipsoid are made equal, the integrals for l_a, l_b, and l_c reduce to the following expressions:—

Oblate spheroid:

$$a < b = c$$

$$\text{Eccentricity} = e = \sqrt{\left(1 - \frac{a^2}{c^2}\right)} = \sqrt{\left(1 - \frac{a^2}{b^2}\right)}$$

$$l_a = 4\pi\left\{\frac{1}{e^2} - \left[\frac{\sqrt{(1 - e^2)}}{e^3}\text{ arc sin } e\right]\right\} \quad . \quad (23)$$

$\simeq 4\pi$, when a is much smaller than b or c.

$$l_b = l_c = 2\pi\left\{\left[\frac{\sqrt{(1 - e^2)}}{e^3}\right]\text{arc sin } e - \left(\frac{1 - e^2}{e^2}\right)\right\} \quad (24)$$

$\simeq \pi^2\frac{a}{b}$, when a is much smaller than b or c.

Prolate spheroid:

$$a > b = c$$

$$\text{Eccentricity} = e = \sqrt{\left(1 - \frac{b^2}{a^2}\right)} = \sqrt{\left(1 - \frac{c^2}{a^2}\right)}$$

$$l_a = 4\pi\left(\frac{1}{e^2} - 1\right)\left(\frac{1}{2e}\log\frac{1+e}{1-e} - 1\right) \quad . \quad (25)$$

$$\simeq 4\pi\frac{b^2}{a^2}\left(\log\frac{2a}{b} - 1\right) \quad . \quad . \quad . \quad . \quad (26)$$

when a is much greater than b or c.

$$l_b = l_c = 2\pi\left(\frac{1}{e^2} - \frac{1-e^2}{e^2}\log\frac{1+e}{1-e}\right) \quad . \quad (27)$$

$\simeq 2\pi$, when a is much greater than b or c.

If the spheroid becomes a sphere, $a = b = c$, and $l_a = l_b = l_c = \frac{4\pi}{3}$.

For convenience, the quantity $n = 4\pi/l_a$ is used in most of the discussion in the paper. n is plotted as a function of the ratio of the axes in Fig. 8.

APPENDIX 2

Properties of a Model Inhomogeneous Dielectric containing Spheroidal Particles

To determine the dielectric constant of the model inhomogeneous material described in Section (3), one can equate the mean polarization of the material in a given field to that of a homogeneous material of dielectric constant κ in the same field, and hence find κ. This can be done as follows.

Consider a spheroidal volume w of the inhomogeneous material surrounded by the pure continuous medium of dielectric constant κ_1, and under the influence of a uniform field ϵ. The total volume of conducting spheroids in w is $q \times w$. The potential at a distant point due to these is proportional to

$$\epsilon\frac{(\kappa_2 - \kappa_1)qw}{4\pi\kappa_1 + (\kappa_2 - \kappa_1)l_a}$$

from equation (22), Appendix 1.

If we regard the mass of inhomogeneous material as having a dielectric constant κ we can equate this expression to

$$\epsilon\frac{(\kappa - \kappa_1)w}{4\pi\kappa_1 + (\kappa - \kappa_1)l'_a}$$

where l'_a corresponds to the shape of the spheroidal volume of mixture. It has been assumed throughout the analysis that κ is not very different from κ_1, so that $(\kappa - \kappa_1)l'_a$ can be neglected in comparison with $4\pi\kappa_1$ and we can put

$$\epsilon\frac{(\kappa - \kappa_1)w}{4\pi\kappa_1} = \epsilon\frac{(\kappa_2 - \kappa_1)qw}{4\pi\kappa_1 + (\kappa_2 - \kappa_1)l_a}$$

whence
$$\kappa = \kappa_1\left[1 + \frac{4\pi q(\kappa_2 - \kappa_1)}{4\pi\kappa_1 + (\kappa_2 - \kappa_1)l_a}\right]$$

$$= \kappa_1\left[1 + \frac{nq(\kappa_2 - \kappa_1)}{(n-1)\kappa_1 + \kappa_2}\right]$$

where $n = 4\pi/l_a$, as before.

Substituting now

$$\kappa = (\kappa' - j\kappa''), \quad \kappa_1 = \kappa'_1, \quad \kappa_2 = \kappa'_2 - j\kappa''_2,$$

we have

$$\kappa' - j\kappa'' = \kappa'_1\left[1 + \frac{nq(\kappa'_2 - \kappa'_1 - j\kappa''_2)}{(n-1)\kappa'_1 + \kappa'_2 - j\kappa''_2}\right]$$

Dividing by κ''_2, and substituting for $\omega\tau$ from equation (7), page 387,

$$\kappa' - j\kappa'' = \kappa'_1\left[1 - nq\frac{\frac{\kappa'_2 - \kappa'_1}{(n-1)\kappa'_1 + \kappa'_2}\omega\tau - j}{\omega\tau - j}\right]$$

$$= \kappa'_1\frac{\left[\frac{nq(\kappa'_2 - \kappa'_1)}{(n-1)\kappa'_1 + \kappa'_2} + 1\right]\omega\tau - j\kappa'_1(nq+1)}{\omega\tau - j}$$

Substituting from equations (8) and (15), and noting that

$$\kappa'(qn + 1) = \kappa'_1 N + \kappa_\infty$$

we get
$$\kappa' - j\kappa'' = \frac{\kappa_\infty\omega\tau - j(\kappa'_1 N + \kappa_\infty)}{\omega\tau - j}$$

which reduces to

$$\kappa' - j\kappa'' = \kappa_\infty + \frac{\kappa'_1 N}{\omega^2\tau^2 + 1} - j\frac{\kappa'_1 N\omega\tau}{\omega^2\tau^2 + 1}$$

whence
$$\kappa' = \kappa_\infty + \frac{\kappa'_1 N}{\omega^2\tau^2 + 1} \quad . \quad . \quad . \quad . \quad (28)$$

$$\kappa'' = \frac{\kappa'_1 N\omega\tau}{\omega^2\tau^2 + 1} \quad . \quad . \quad . \quad . \quad (29)$$

$$\tan\delta = \frac{\kappa'_1 N\omega\tau}{\kappa_\infty\omega^2\tau^2 + \kappa'_1 N + \kappa_\infty} \quad . \quad . \quad (30)$$

These expressions have already been discussed in Section (3) of this paper.

REFERENCES

(1) (*a*) K. W. WAGNER: *Archiv für Elektrotechnik*, 1914, vol. 2, p. 371.
(*b*) H. SCHERING: "*Die Isolierstoffe der Elektrotechnik*" (Springer, Berlin, 1924).
(2) See, for example:—
(*a*) E. VON SCHWEIDLER: *Annalen der Physik*, 1907, vol. 24, p. 711, *or*
(*b*) K. W. WAGNER: *ibid.*, 1913, vol. 40, p. 817, *or*
(*c*) L. HARTSHORN: *Journal I.E.E.*, 1926, vol. 64, p. 1177.
(3) See, for example:—
(*a*) D. DU BOIS: *Transactions of the American I.E.E.*, 1922, vol. 41, p. 591.
(*b*) E. J. MURPHY: *Journal of Physical Chemistry*, 1929, vol. 33, p. 200.
(4) K. W. WAGNER: See page 387 of Reference (1)*a*.
(5) K. W. WAGNER: *Archiv für Elektrotechnik*, 1914, vol. 3, p. 100.
(6) C. LUBBEN: *ibid.*, 1921, vol. 10, p. 283.
(7) (*a*) E. B. MOULLIN: "Radio Frequency Measurements," p. 273 *et seq.* (Griffin, 1931).
(*b*) E. B. MOULLIN: *Wireless Engineer*, 1930, vol. 7, p. 367.
(8) For a complete description of the condensers used, see W. JACKSON: *Proceedings of the Royal Society*, A, 1933, vol. 142, p. 608.
(9) J. A. LEE and H. H. LOWRY: *Journal of Industrial and Engineering Chemistry*, 1927, vol. 19, p. 302.
(10) S. EVERSHED: *Journal I.E.E.*, 1914, vol. 52, p. 63.

THE TRANSMISSION OF ALTERNATING-CURRENT POWER WITH SMALL EDDY-CURRENT LOSSES*

By A. H. M. ARNOLD, D.Eng., Associate Member.

[From the National Physical Laboratory.]

(*Paper first received* 28*th July, and in final form* 23*rd November*, 1936.)

SUMMARY

A method is outlined of designing single-phase conductors with small eddy-current losses. Experimental results are given verifying the theory and the accuracy of the formula for calculating the eddy-current losses.

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(1) INTRODUCTION

The problem considered in this paper is the transmission of alternating-current power along a single-phase system of two conductors with the minimum of eddy-current losses due to the non-uniform distribution of current across the section of the conductors. The two conductors are assumed straight, parallel, and of uniform and equal sections, and, further, the dielectric current is assumed to be negligible, so that the lines of current flow are normal to the section. The problem is then purely two-dimensional, since the shape, size, and disposition of the sections are the only variables in space. The conductor current is assumed to vary sinusoidally with respect to time.

It is well known that the non-uniform distribution of current across the section of a conductor results from the unequal inductances of the various filaments of the conductor. If it were possible to shape the section so that all filaments had equal inductance there would be no eddy-current loss. Such a section does not exist. If, however, the section be represented by a line, and it is assumed that the dimension of the section normal to the line, the thickness, is infinitely small, then it is possible to find two lines, representing the sections of the "go and return" conductors of a single-phase system, which satisfy the requirement of equal inductance of all their parts. Such lines will be termed equi-inductance lines.

The ratio of the shortest distance between the lines to the arc-length† of each line is defined by the symbol α. For each value of α there is one shape of equi-inductance line only.

It is of interest to note that when two conductors, shaped in accordance with equi-inductance lines, are oppositely electrified, the surface stress is uniform over the whole surface of each conductor.

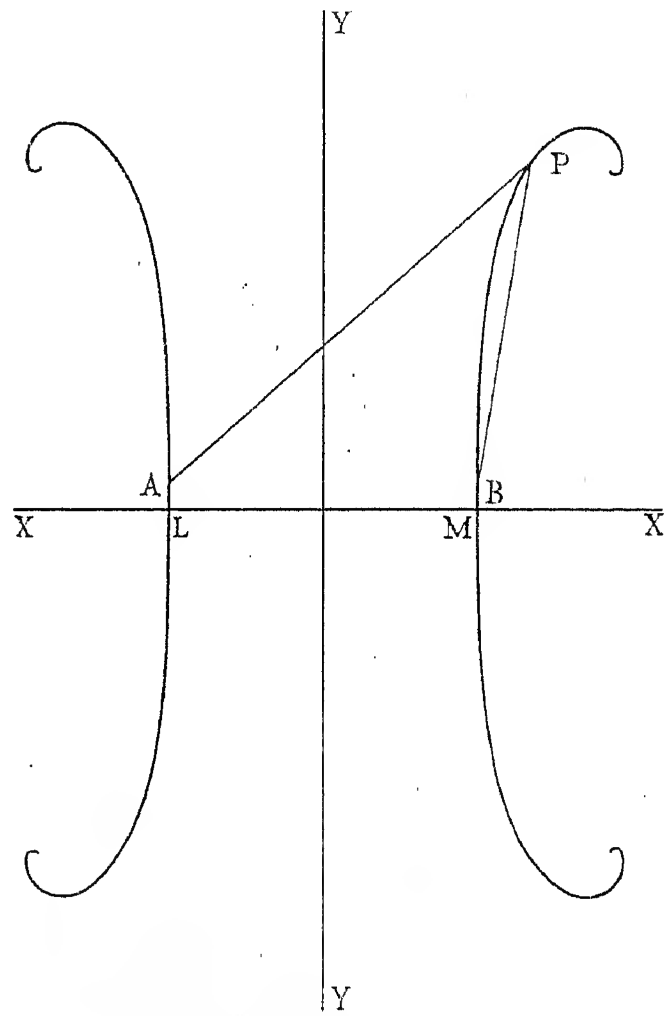


Fig. 1.—Equi-inductance lines.

$$\left.\begin{array}{r}\text{Arc-length of each line} = s\\ \text{Minimum separation between lines} = \text{LM}\end{array}\right\}\alpha = \text{LM}/s$$

(2) EQUI-INDUCTANCE LINES FOR SINGLE-PHASE SYSTEMS

Fig. 1 shows two equi-inductance lines for a single-phase system. Conditions of symmetry require that these lines shall be symmetrical about the axes XX and YY.

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† The term "arc-length" is used for the length of the equi-inductance line ni order to distinguish this dimension from the length of the conductor.

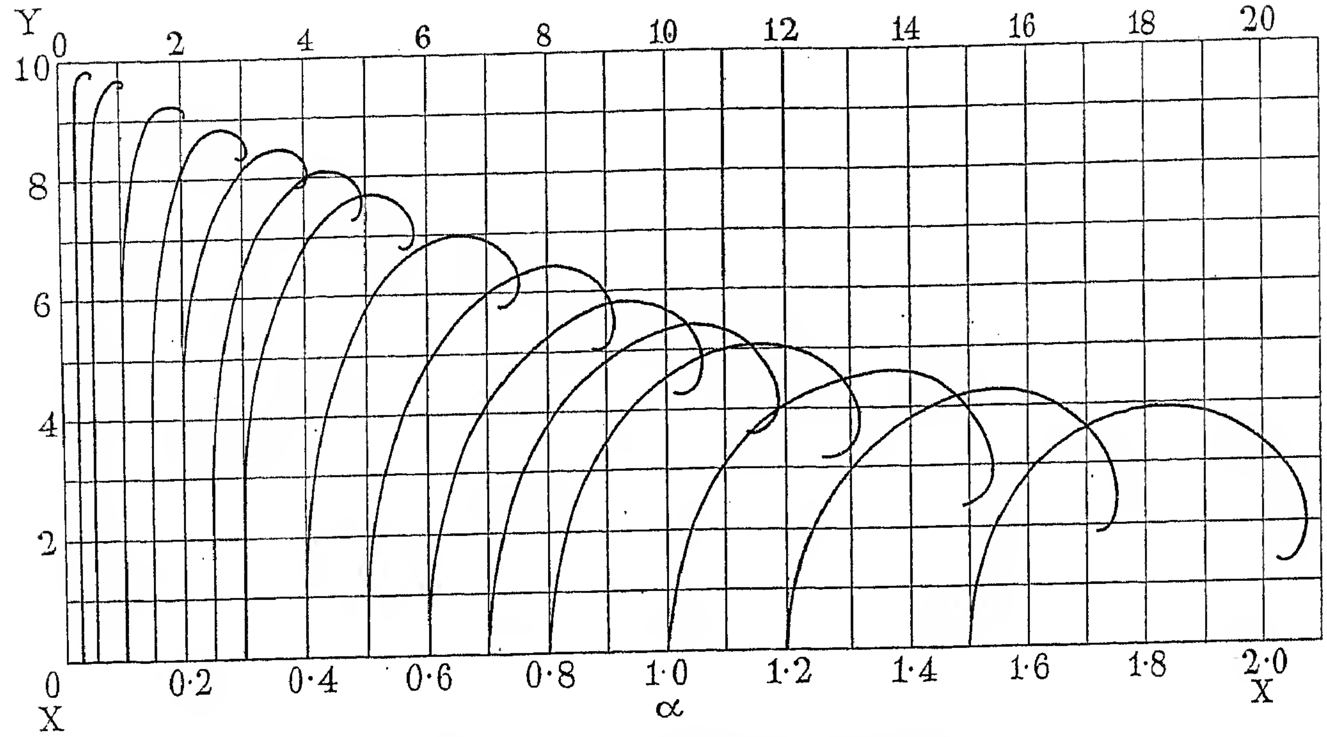


Fig. 2.—Family of equi-inductance lines.

The lines are all of equal arc-length and are drawn in their correct positions relative to the axes of symmetry XX and YY.

The inductance of a small element of the line at the point P is equal to the sum of the mutual inductances of all the elements of both the lines with the small element at P, or, in symbols,

$$\text{Inductance at P} = \frac{2}{s}\int_0^s \log \frac{\text{AP}}{\text{BP}} ds \quad . \quad . \quad . \quad (1)$$

where A and B move over the whole arc-length (s) of their respective lines. If the integral in equation (1) has the same numerical value for any position of P on the line, then the line will be an "equi-inductance" line.

The author has been unable to find a solution of equation (1) in terms of known functions, but the required equi-inductance lines have been obtained by a process of approximate integration and successive approximations. The family of lines over a range of α from 0·025 to 1·5 is shown in Fig. 2. Only one half-line is shown, as the other half is symmetrical. It may be seen that when α is very small, corresponding to a small spacing, the lines approximate to two parallel straight lines. When α is large, corresponding to a large spacing, the lines approximate to circles, finally reaching the circular shape when $\alpha = \infty$.

(3) EFFECT OF FINITE THICKNESS OF CONDUCTORS

Conductor sections must have finite area, and therefore can only approximate to an equi-inductance line which has no area. The approximation may be made as close as is desired by making the thickness of the section very small, and the dimension normal to the thickness a close approximation to the shape of an equi-inductance line. The inductances of the elementary filaments of the conductor will then be very nearly equal and the eddy-current losses will be very small.

Experimental results given later in the paper show that the losses in a conductor, shaped approximately to an equi-inductance line, may be calculated within a few per cent from a formula for the eddy-current losses in an

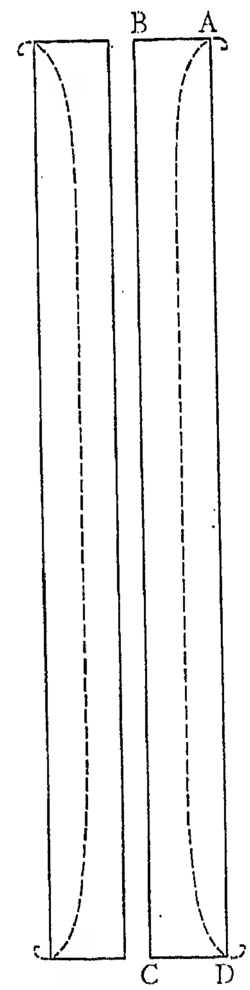


Fig. 3.—Rectangular sections for close spacings.

Equi-inductance lines shown dotted.

isolated tubular conductor, provided that an appropriate modification is made in the definition of one of the terms. Such a formula has already been published by the

author* for the case of a tubular conductor remote from all other conductors, and is reproduced here for convenient reference. It is:—

$$\frac{R'}{R} = 1 + a(z)(1 - \tfrac{1}{2}\beta) \quad . \quad . \quad . \quad . \quad (2)$$

in which R' = alternating-current resistance of conductor, R = direct-current resistance of conductor, $\beta = 2t/d$, t = thickness of conductor (cm.), $= \frac{1}{2}$ (outside diameter—inside diameter), d = outside diameter of conductor (cm.), $a(z)$ is a function of z, $z = 8\pi^2 t^2 f\sigma$, f = frequency (cycles per sec.), and σ = conductivity of conductor (c.g.s. units).

As the two conductors of a single-phase system of tubular conductors are brought nearer together from an infinite distance apart, the eddy-current losses increase on account of proximity effect. If, however, at the same time, the shapes of the sections are altered so that they always approximate to the equi-inductance lines corresponding to the spacing between conductors, then no proximity effect will be introduced, and equation (2) may be used to calculate the eddy-current losses for all spacings between conductors. A new definition of β is, however, required.

For the tube,

$$\beta = 2t/(\text{Outside diameter of tube})$$
$$= 2\pi t/(\text{Outside circumference of tube})$$

For section shaped approximately to the equi-inductance lines,

$$\beta = 2\pi t/(\text{Arc-length of section measured on side nearest to return conductor})$$

* *Journal I.E.E.*, 1936, vol. 78, p. 582, equation (3). The more precise equation (9) is not required in this work.

Since the section is shaped only approximately to an equi-inductance line, equation (2) can only be used, provided the value of R'/R is fairly small. It has been found experimentally that the equation is correct within a few per cent, provided z is not greater than 10 or R'/R is not greater than 2. For this range of z the following simple approximate formula for $a(z)$ may be used:—

$$a(z) = \frac{7z^2}{315 + 3z^2 - 0\cdot 002z^4} \quad . \quad . \quad . \quad (3)$$

At a frequency of 50 cycles per sec., z does not exceed 10 if the thickness is less than $2\cdot 2$ cm.

Equation (3) gives values for $a(z)$ having errors of less than $0\cdot 1$ per cent, provided z is less than 10. Equation (2) may now be written in the form

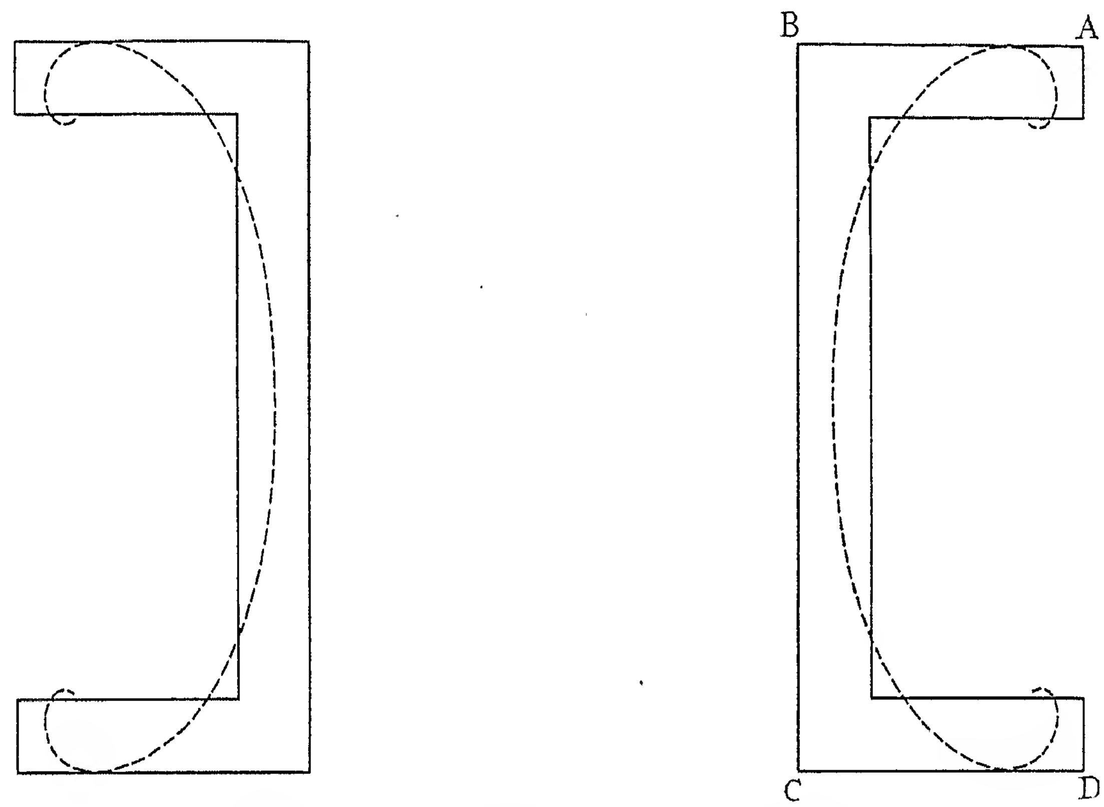


Fig. 4.—Channel sections for moderate spacings.
Equi-inductance lines shown dotted.

$$\frac{R'}{R} = 1 + \frac{7z^2(1 - \frac{1}{2}\beta)}{(315 + 3z^2 - 0\cdot 002z^4)} \quad . \quad . \quad (4)$$

For values of z above 10, equation (2) should be used, and the value of $a(z)$ should be obtained from Table 1 in the previous paper;* but the error of the equation may be rather large.

A conductor with a section shaped approximately to an equi-inductance line has minimum loss for a given thickness, but the loss increases slowly as the shape departs from the true shape. A certain amount of deformation will not appreciably affect the validity of equation (4), and at the same time may enable a simpler section to be obtained. Experience alone is the best guide to the amount of deformation permissible, but as a rough rule it may be taken that the average distance between the centre line of the section and the equi-inductance line should not exceed the thickness of the

* *Loc. cit.*

conductor, and the maximum distance should not exceed twice the thickness of the conductor. With this rule in mind, and provided β, the ratio of 2π times the thickness of the conductor to the length of the section, is not less than about 0·15, it will be found that one of three simple sections can be used for all spacings between conductors. When the spacing is small, α lying between 0 and 0·3, a rectangular section is a sufficiently close approximation to an equi-inductance section. Fig. 3 shows an example, with the equi-inductance line drawn as a dotted line. For rectangular sections β may be taken as 2π times the thickness divided by the sum of one long side and two short sides, i.e. $2\pi t/$(Length ABCD in Fig. 3). For moderate spacings, α lying between 0·2 and 0·7, a channel section, as shown in Fig. 4, may be used. For channel sections β may be taken as 2π times the thickness divided by the sum of the three longest sides, i.e. $2\pi t/$(Length ABCD in Fig. 4). For large spacings, with α greater than 0·6, the tubular conductor may be used. Table 1 shows the advantages and disadvantages of each section.

Table 1

	Rectangular section, close spacings	Channel section, moderate spacings	Tubular section, large spacings
(1)	Low inductance	Moderate inductance	Large inductance
(2)	Little rigidity for resisting short-circuit forces	Great rigidity for resisting short-circuit forces	Great rigidity for resisting short-circuit forces
(3)	Large surface area for dissipating heat	Large surface area for dissipating heat	The inner surface will not be able to dissipate heat quickly
(4)	Heat dissipation may be reduced on account of proximity of return conductor	Heat dissipation unaffected by return conductor	Heat dissipation unaffected by return conductor

(4) EXPERIMENTAL WORK

Experimental measurements of eddy-current losses were made on three conductor sections of copper. The conductors employed were each 20 ft. long. Two pairs of conductors had rectangular sections with a ratio of depth to thickness of 16 to 1 and 8 to 1 respectively. The third pair of conductors had a channel section.

The experimental method employed was the same as that used for measuring the eddy-current losses in solid and tubular conductors, and has already been described.* The conductors of rectangular cross-section may be considered to approximate to the equi-inductance lines for zero spacing between conductors, and minimum loss may therefore be expected when the conductors are close together. The dimensions of the channel section are shown in Fig. 6, and this section approximates closely to an equi-inductance line if the separation between conductors is 4·3 cm. The results obtained when the conductors were tested at these spacings are shown in Table 2, and it may be seen that the greatest discrepancy between the experimental results and the calculations by equation (4) is 3 per cent. The range of frequency employed to obtain different values of $\alpha(z)$ was from 25 cycles per sec. to 600 cycles per sec.

In the curves, Figs. 5 and 6, the effect of altering the spacing between the conductors from the correct spacing for theoretical minimum loss is shown. At low frequencies the eddy-current losses are increased in accordance with theory. At high frequencies, minimum loss occurs at a spacing somewhat greater than the theoretically correct spacing. The effect is most pronounced in the case of the rectangular conductors. At high frequencies the current is concentrated mostly on the surface of the conductors, and the effect can be explained in this manner: When the conductors are very close together the current is concentrated only on the close surface of the conductor nearest to the return conductor and the two end surfaces. As the separation is increased,

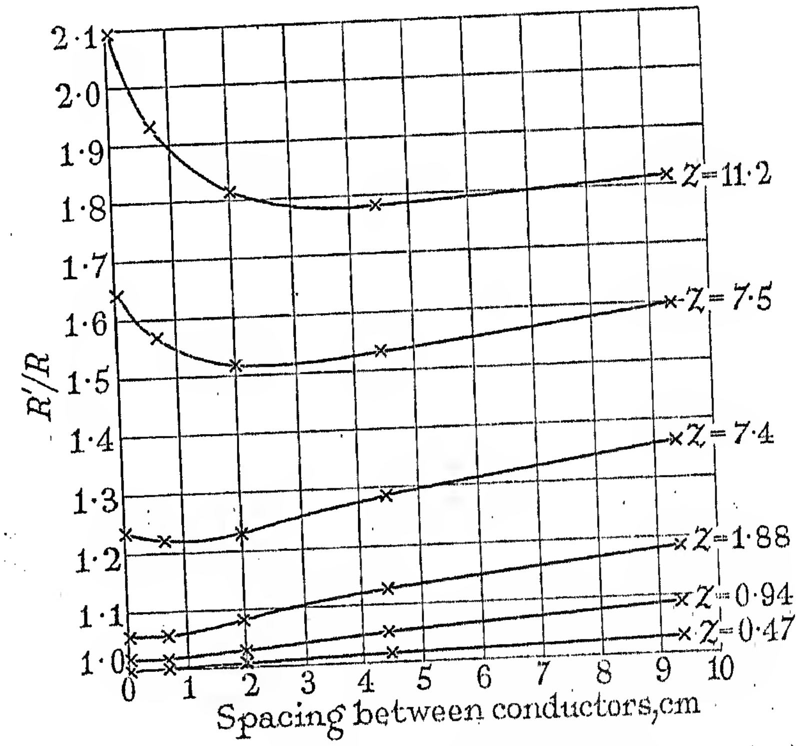


Fig. 5.—Values of R'/R for rectangular-section conductor with varying spacing between conductors.

Spacing for theoretical minimum loss is zero.
Experimental points shown by crosses.
Conductor-section dimensions 10·17 cm. × 0·637 cm.

it may be seen from the equi-inductance lines that some of the current will tend to flow on the surface of the conductor farthest from the return conductor near to the ends. Thus the effective section will be slightly increased, with a resultant fall in eddy-current losses. A similar explanation applies to the channel sections, although the effect is less pronounced.

* *Journal I.E.E.*, 1935, vol. 77, p. 55; and 1936, vol. 78, p. 588.

In designing a system of conductors, therefore, the actual separation should be made greater than that indicated by the equi-inductance lines, if the calculated value of R'/R is high.

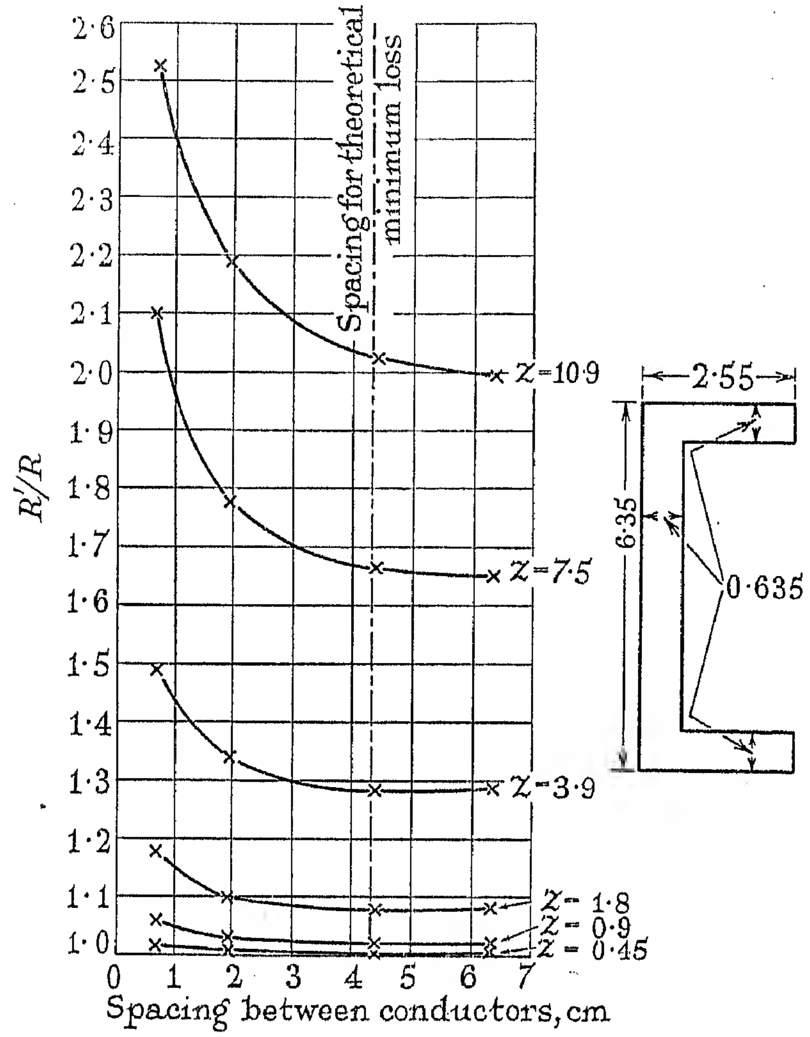


Fig. 6.—Values of R'/R for channel-section conductors with varying spacing between conductors.

Spacing for theoretical minimum loss = 4·3 cm.
Experimental points shown by crosses.

(5) DESIGN OF CONDUCTORS FOR SINGLE-PHASE SYSTEMS

Theory

If all the dimensions of the conductors are fixed except the thickness, and the thickness is gradually increased from zero, the alternating-current resistance will fall, reach a minimum, then rise, and will finally oscillate with ever-decreasing amplitude of oscillation about a fixed value. It is clear that it is useless to add further copper after the first minimum resistance has been reached, since none of the succeeding minima is as low as the first, and the thickness of conductor which gives this first minimum resistance should never be exceeded in any design. A lesser thickness may, of course, often be employed advantageously.

With the thickness as the only variable, the direct-current resistance of a conductor is inversely proportional to the thickness, and therefore inversely proportional to the square root of z. From equation (4), therefore, we may write,

$$R' = \frac{k}{\sqrt{z}}\left\{1 + a(z)[1 - \tfrac{1}{2}\beta]\right\}, \text{ where } k \text{ is a constant} \quad . \quad (5)$$

By a few trial calculations it is found that the minimum value of R' occurs when z is greater than 4.

A very simple equation, accurate to 2 decimal figures, may be used for $a(z)$ when z lies between 4 and 9. This equation is:—

$$a(z) = \frac{3}{20}(z - 2) \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Inserting this value into equation (5), we have

$$R' = \frac{k}{\sqrt{z}}\left[1 + \frac{3}{20}(z - 2)(1 - \tfrac{1}{2}\beta)\right] \quad . \quad . \quad (7)$$

Table 2

z	$a(z)$	A = Theoretical value of R'/R, calc. from $1 + a(z)(1 - \frac{1}{2}\beta)$	B = Experimental value of R'/R	B/A
(1) *Rectangular section* 10·17 *cm.* × 0·637 *cm.*, β = 0·35, *separation between conductors* 0·03 *cm.*				
0·469	0·005	1·004	1·003	$0{\cdot}99_9$
0·938	0·020	1·016	1·014	$0{\cdot}99_8$
1·875	0·076	1·063	1·058	$0{\cdot}99_5$
3·99	0·308	1·254	1·237	$0{\cdot}98_6$
7·48	0·822	1·678	1·649	$0{\cdot}98_3$
11·21	1·326	2·095	2·094	$1{\cdot}00_0$
(2) *Rectangular section* 10·17 *cm.* × 1·274 *cm.*, β = 0·63, *separation between conductors* 0·02 *cm.*				
1·864	0·075	1·051	1·051	$1{\cdot}00_0$
3·73	0·273	1·187	1·184	$0{\cdot}99_7$
7·46	0·819	1·561	1·570	$1{\cdot}00_6$
(3) *Channel section* 6·35 *cm.* × 2·55 *cm.* × 0·635 *cm.* (*outside dimensions*), β = 0·35, *separation between conductors* 4·39 *cm.*				
0·456	0·005	1·004	1·004	$1{\cdot}00_0$
0·912	0·018	1·015	1·021	$1{\cdot}00_6$
1·824	0·072	1·059	1·079	$1{\cdot}01_9$
3·88	0·292	1·241	1·280	$1{\cdot}03_1$
7·29	0·794	1·655	1·664	$1{\cdot}00_5$
10·91	1·290	2·065	2·028	$0{\cdot}98_2$

Thus

$$\frac{dR'}{dz} = -\tfrac{1}{2}kz^{-\frac{3}{2}}\left[1 + \frac{3}{20}(z - 2)(1 - \tfrac{1}{2}\beta)\right] + \frac{3}{20}kz^{-\frac{1}{2}}(1 - \tfrac{1}{2}\beta)$$

The minimum value of R' is obtained when $dR'/dz = 0$, i.e. when

$$z = \frac{2}{3}\left(\frac{14 + 3\beta}{2 - \beta}\right) \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Table 3 shows the values of z, $a(z)$, and R'/R, for the minimum value of R'.

The permissible thickness of conductor is therefore dependent on the value of β. An example will now be given to show the method of design suggested.

Example: To Design a Single-phase System of Conductors for a Frequency of 50 cycles per sec. with an Effective Conductor Section of 10 sq. in.

First approximation.

Assume $R'/R = 1\cdot5$. Then copper section required $= 15$ sq. in. Assuming a temperature-rise of 30 deg. C. from an ambient temperature of 20° C.,

$$\text{Conductivity of copper} = \sigma = 0\cdot00052 \text{ c.g.s. units}$$

$$\text{Thickness of section} = t = \frac{1}{2\pi}\sqrt{\left(\frac{z}{2f\sigma}\right)}$$
$$= 0\cdot698\sqrt{z}$$

For $z = 5$, $t = 1\cdot56$ cm.; for $z = 9$, $t = 2\cdot09$ cm. Assume $t = \frac{11}{16}$ in. $= 1\cdot75$ cm. Then mean arc-length of section $= 22$ in., and

$$\beta = \frac{2\pi \times \frac{11}{16}}{22} = 0\cdot20$$

Adopting a value of α of $0\cdot6$, Fig. 7 shows a suitable channel section, with the equi-inductance line for $\alpha = 0\cdot6$ fitted to it.

The necessary separation between the conductors is

Table 3

Values of z, a(z), and R'/R, for minimum value of R'

β	z	$a(z)$	R'/R
0	4·67	0·40	1·40
0·1	5·10	0·47	1·42
0·2	5·41	0·51	1·46
0·3	5·84	0·58	1·49
0·4	6·34	0·65	1·52
0·5	6·89	0·73	1·55
0·6	7·52	0·83	1·58
0·7	8·26	0·94	1·61
0·8	9·11	1·07	1·64

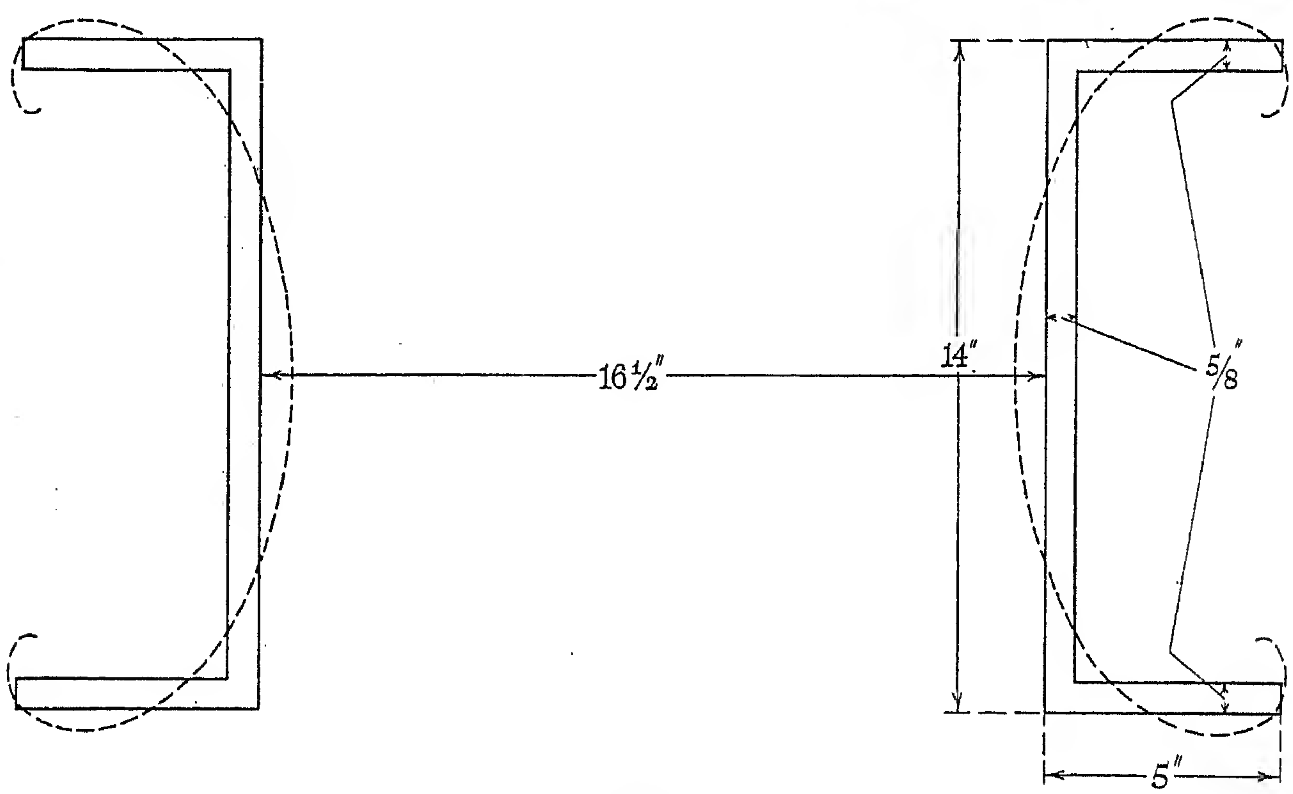


Fig. 7

Second approximation.

For $\beta = 0\cdot20$, minimum R' occurs when $z = 5\cdot4$, i.e. when $t = 1\cdot62$ cm. Take $t = \frac{5}{8}$ in. $= 1\cdot59$ cm. Then mean arc-length of section $= 24$ in.

The designer now has to choose his section. A rectangular section, 24 in. $\times \frac{5}{8}$ in., would be very awkward to handle. The tubular conductor would be most compact, but the necessary separation between conductors to minimize proximity losses would be large, and the heat dissipation from the inner surface poor. The channel section offers the most advantages in this case, and it could be made in three or more pieces of rectangular section, if desired.

The value of α has next to be selected. If α is taken too small, the channel section will be little more compact than the rectangular section, while if α is taken too large it is difficult to fit the section to the equi-inductance line.

seen from Fig. 7 to be $16\frac{1}{2}$ in. The actual effective section obtained with these conductors will now be worked out.

$$\text{Copper section} = (14 \times \tfrac{5}{8}) + (4\tfrac{3}{8} \times \tfrac{5}{8} \times 2) \text{ sq. in.}$$
$$= 14\cdot2 \text{ sq. in.}$$

$$\beta = \frac{2\pi \times \frac{5}{8}}{24} = 0\cdot16$$

$$z = 8\pi^2 \times 1\cdot587^2 \times 50 \times 0\cdot00052 = 5\cdot17$$
$$a(z) = 0\cdot48$$
$$R'/R = 1\cdot44$$

Effective copper section $= 14\cdot2/1\cdot44 = 9\cdot9$ sq. in.

If a smaller spacing between conductors is required, then it will be necessary to shorten the two short sides of the channel, and lengthen the long side.

MODERN RECEIVING VALVES: DESIGN AND MANUFACTURE

By M. BENJAMIN, B.Sc., Ph.D., C. W. COSGROVE, B.Sc., Associate Member, and G. W. WARREN, B.Sc.

[Communication from the Research and Engineering Staffs of the M.O. Valve Co., Ltd., at the Works, Hammersmith, and (G.E.C.) Research Laboratories, Wembley, England.]

(*Paper first received 4th August*, 1936, *in revised form 23rd October*, 1936, *and in final form 23rd February*, 1937; *read before the* WIRELESS SECTION *2nd December*, 1936.)

SUMMARY

The authors discuss the main features in the geometrical design of the types of valve in common use to-day and the various factors, mechanical and chemical, which impose limitations in manufacture. The minimum tolerances to which it is possible to reproduce characteristics are indicated. The paper includes a brief historical survey of the recent improvements in thermionic emitters and gives details of the precautions necessary in the production of modern highly efficient oxide-coated cathodes and insulated heaters.

Pumping and activation processes are described, and the main factors affecting the life of a valve are discussed. The last section of the paper deals with some of the limitations encountered in the use of valves, such as hum, microphony, noise, and frequency limitation, and the methods of minimizing these factors are given. The authors conclude with some observations on possible future developments.

INTRODUCTION

During the past 10–15 years, the efforts of valve manufacturers have been directed towards increasing the efficiency of receiving valves by the development of special types for specific purposes, and towards the improvement of the characteristics of valves by modifications in the mechanical design, improvements in thermionic cathodes, and a close control of the properties of materials used for electrodes and insulators. A study of the causes and methods of reducing "noise" has also received considerable attention.

The fluctuating demand for valves of different types makes it difficult for the valve manufacturer to plan production in advance over long periods and so to ensure that continuity which is desirable in any mass production. Developments in radio-receiver design are continually calling for new types of valve and for modifications to existing valves, and the manufacturing plant must be sufficiently flexible to allow changes to be effected rapidly. In spite of this, however, the enormous increase in production and improvements in technique during the past 10 years have led to considerable reductions in manufacturing costs with the result that a modern complex valve, such as, for example, a triode hexode with an indirectly heated cathode, is sold at approximately the same price as was a simple triode with a filamentary cathode in 1924.

Until about 1924 the only type of valve in common use was the triode with a filamentary cathode. These valves were designed with high or low amplification factor and impedance according to the particular position in the receiver in which they were required to operate. Provided the cathode was capable of giving sufficient emission, and the grid current, with the grid at a negative potential with respect to the cathode, was not more than a few microamps., the valve was "good." Output valves were in general required to generate only a few milliwatts, sufficient to load a pair of headphones, although it is true that there were some high-priced valves capable of delivering several watts for loud-speaker use. Owing to the limitations inherent in loud-speakers at that time, and to the poor characteristics of intervalve transformers, the amount of distortion introduced by the valve itself was relatively unimportant.

In 1916 Siemens and Halske* patented a tetrode valve in which a fourth electrode in the form of a grid or "protective net" was interposed between the control grid and anode, and operated at a fixed positive potential with respect to the cathode. The object of this "protective net" was to prevent the field near the cathode from being influenced by changes in the potential of the anode.

In the Schottky tetrode† the fourth electrode did, in fact, provide slight electrostatic screening between anode and control grid, but it was not until after A. W. Hull‡ had suggested the introduction of a close-mesh screen electrode in order to reduce the feed-back of alternating potentials on the anode to the grid, which resulted in serious interference between output and input circuits at high frequencies, that the screen-grid could be used for high-frequency amplification.

The introduction of a fourth electrode operating at a positive potential introduced secondary-emission difficulties hitherto absent from receiving valves. In 1926, the Philips Lamp Co. of Holland§ described two methods of suppressing the secondary currents between anode and screen: (*a*) by removing the anode to a sufficient distance from the screen, and (*b*) by the introduction of an open-meshed grid in order to reduce the space potential between screen and anode. This second alternative, the Pentode valve, was used in the first instance only as a low-frequency output valve, but more recently high-frequency pentode valves—differing from output pentodes in the degree of screening between anode and control grid—have been used as high-frequency amplifiers and detectors.

In order to enable the output of a receiver to be adjusted to any desired level without distortion when

* See Reference (1). † *Ibid.*, (2). ‡ *Ibid.*, (3), (4). § *Ibid.*, (5).

receiving strong or weak signals, screen-grid and high-frequency pentode valves having a variable mutual conductance (variable-mu) depending on the control-grid bias were later introduced.* There are several possible methods of obtaining the required characteristic, but the one now universally adopted is to vary the pitch of the control-grid winding or to introduce gaps in the winding so that over a small length of the cathode surface the grid has little effect on the field. The "tail" of the anode-current/grid-voltage characteristic is modified as shown in Fig. 1. The required shape of the variable-mu characteristic depends to some extent on the particular circuit in which the valve is to be used, and in practice a compromise must be effected between high control ratio and the maximum permissible anode current at zero grid bias and the maximum grid bias obtainable in the circuit. These conditions having been decided, the actual design of the grid is a matter of trial and experience.

Diode valves, which were until recently used only as

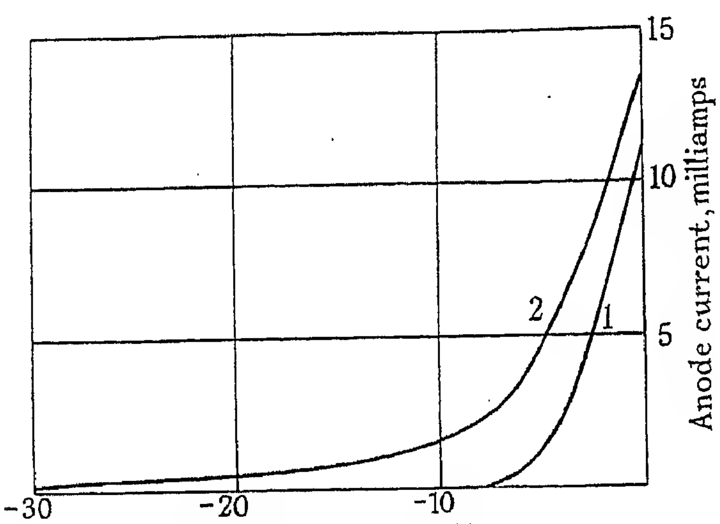


Fig. 1

Curve 1. Grid wound with uniform pitch.
Curve 2. Grid wound with gaps in grid winding.

power rectifiers for a.c. mains supply voltages, are now frequently employed as high-frequency detectors and, by a suitable arrangement of circuits, for automatically controlling the grid bias on variable-mu valves so that the output from the receiver can be kept at a substantially constant level. These applications have resulted in the introduction of further types, such as double diodes, double diode triodes, and double diode pentodes.

The rapidly increasing popularity of the super-heterodyne receiver, which is becoming even more extensively employed in short-wave reception, has led to the introduction of improved forms of frequency-changers by means of which it is possible to obtain a much greater conversion conductance and greater stability than was possible in earlier forms of valves. The most recent types include hexodes, heptodes, octodes, and double valves such as triode pentodes and triode hexodes.

It is not within the scope of this paper to describe the many circuits used in conjunction with various types of valves; the authors' object is rather to outline the main features in the design of the valves, and to indicate the limitations met in practice. For this purpose it is necessary to consider the types in more detail.

* See Reference (6).

DIODES

(a) Power Rectifiers

The principal requirements in a power rectifier are a low impedance when the anode is at a positive potential with respect to the cathode, so that the voltage across the rectifier shall be small compared with that across the external circuit, and a high impedance when the voltage is reversed.

If we consider the simple case of a cathode of circular section surrounded by a cylindrical anode, the space-charge-limited anode current is*

$$i = \frac{KlV_a^{\frac{3}{2}}}{a\beta^2} \text{ (approx.)} \quad . \quad . \quad . \quad . \quad (1)$$

where l is the length of the system, and

$$\beta = \log\frac{a}{c} - \frac{2}{5}\left(\log\frac{a}{c}\right)^2 + \frac{11}{120}\left(\log\frac{a}{c}\right)^3 \quad . \quad . \quad (2)$$

a and c being the radii of anode and cathode respectively. V_a is the positive potential of the anode with respect to the cathode, and K is a constant.

It therefore follows that the impedance may be reduced by increasing l or decreasing $a\beta^2$. In directly-heated cathode valves (filamentary cathodes) the cathode length can be made large, and little difficulty is experienced in reducing the voltage-drop across the rectifier. It is, of course, important that, when the filament is in the form of a **V** or **W**, the limbs of the filament shall be sufficiently far apart to act independently of one another. In practice, this means that the distance between limbs shall be at least twice the distance between anode and filament. Directly-heated rectifiers, however, possess the disadvantage that the heating-up time is usually shorter than that of the indirectly heated valves in the set, with the result that the rectifier is open-circuited for a few seconds each time the receiver is switched on, and excessive voltages are developed across condensers. Indirectly-heated rectifiers are therefore necessary in some cases. In indirectly-heated valves, it is difficult to obtain a long cathode, and it is therefore necessary to make the cathode-anode clearance small. There is, however, a limitation (apart from the purely mechanical problem) in the value to which this distance can be reduced, since, as the anode surface is reduced, although the energy of the arriving electrons falls owing to the lower impedance, the temperature rises owing to radiation from the cathode. If the temperature of the anode becomes excessive, it will emit electrons when the anode voltage is reversed, since with oxide-coated cathodes some barium will have been deposited on the anode during activation of the cathode. Apart from the effect of this reverse current on the output of the rectifier, the cathode surface will rapidly be destroyed by bombardment of high-voltage electrons, and the valve become "soft." To keep the temperature of the anode as low as possible, its surface is usually carbonized by a heat treatment in a hydrocarbon atmosphere, thus increasing its thermal emissivity.

* See Reference (7).

Another method which has been employed to reduce the impedance is to include between the anode and cathode, and close to the cathode, an electrode in the form of a grid which is connected to the anode. In this way the system behaves as a diode with an effective anode diameter slightly greater than that of the grid. Most of the energy is, however, dissipated in the outer electrode, which may now be quite large.

In a recent publication* Aldous has shown that, in a rectifier feeding a resistance load shunted by an infinite capacitance, the following equations express quite accurately the values of the power dissipated in the anode (P), the output voltage (V), and the peak anode current ($I_{max.}$), as functions of the peak input voltage (E) and output current (I).

For a single-phase half-wave circuit,

$$P = 1{\cdot}62\, K^{-\frac{1}{2}}E^{\frac{1}{4}}I^{\frac{3}{2}}$$
$$E - V = 1{\cdot}94\, K^{-\frac{1}{2}}E^{\frac{1}{4}}I^{\frac{1}{2}}$$
$$I_{max.} = 2{\cdot}71\, K^{\frac{1}{4}}E^{\frac{3}{8}}I^{\frac{3}{4}}$$

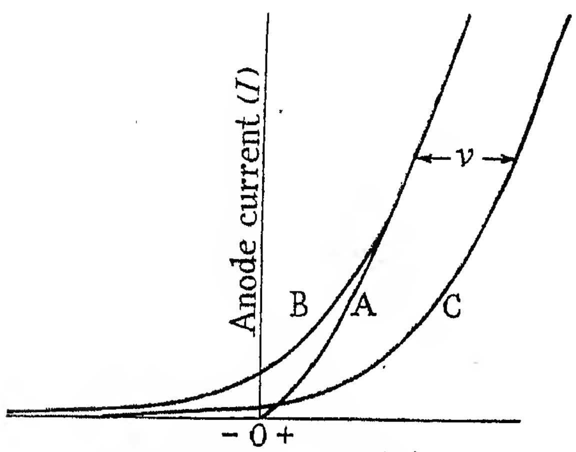


Fig. 2

Curve A. $I = kE^{\frac{3}{2}}$
Curve B. Effect of initial velocities of electrons.
Curve C. Effect of initial velocities and contact potential-difference between anode and cathode.

and, for a biphase half-wave circuit,

$$P = 1{\cdot}14\, K^{-\frac{1}{2}}E^{\frac{1}{4}}I^{\frac{3}{2}}$$
$$E - V = 1{\cdot}37\, K^{-\frac{1}{2}}E^{\frac{1}{4}}I^{\frac{1}{2}}$$
$$I_{max.} = 1{\cdot}61\, K^{\frac{1}{4}}E^{\frac{3}{8}}I^{\frac{3}{4}}$$

where K is the rectifier constant in the equation for the static characteristic of the rectifier, $i = KV_a^{\frac{3}{2}}$.

From these equations, the valve designer is able to estimate the cathode emission required and the minimum dimensions of the anode† for a given rectifier.

(b) Detector Diodes

In the approximate expressions given above, the initial velocities of the electrons and the contact potential-difference between cathode and anode were neglected. The effect of taking into account these factors is shown in Fig. 2. Curve A shows the three-halves power-law relationship of equation (1), curve B shows the effect of the initial velocities of electrons, and curve C the further effect of the contact potential-difference ν between cathode and anode. Expressions have been derived by Schottky,* Fry,† and Langmuir‡ for curve C, but these need not be considered here. It will be apparent that the value of ν is important in determining the characteristic of a detector diode which operates at very low values of anode potential. A change in the nature of the surface of the anode, an alteration in treatment of the cathode during pumping and activation, or the presence of gas, will affect the degree of contamination of the surface of the anode, and may change its contact potential by as much as 2 volts. A close control of all these factors is necessary to ensure reproducible results and stability during operation.

TRIODES

It is not possible to calculate with any great accuracy the characteristics of small receiving valves of given dimensions or, conversely, to determine the dimensions necessary to give any required characteristics. This is due to such factors as end effects, lack of axial symmetry of the electrode system imposed by mechanical considerations and, in most valves, the well-known phenomenon *Inselbildung*, which is due to the fact that the electric field in the neighbourhood of the cathode surface is not uniform along its length.

By making certain assumptions, however, formulae have been obtained by several workers for plane and cylindrical electrode systems (the former is, of course, a limiting case of the latter) and, although only approximate, these are useful in determining qualitatively the effects of the various electrode dimensions and operating conditions on the characteristics of the valve.

Vogdes and Elder§ deduced the following expression for the amplification factor (μ) of a triode in the form of a cylindrical system of electrodes, end effects being neglected:—

$$\mu = \frac{2\pi nb \log \dfrac{a}{b} - \log \cosh 2\pi n\rho}{\log \coth 2\pi n\rho} \quad . \quad . \quad (3)$$

where a is the radius of the anode, b is the radius of the grid, ρ is the radius of the grid wires, and n is the number of turns of the grid per cm. In practice, the second term of the numerator is negligible compared with the first term, and we have

$$\mu \simeq \frac{2\pi nb \log (a/b)}{\log \coth 2\pi n\rho} \quad . \quad . \quad . \quad . \quad (4)$$

The value of the space-charge-limited current (in amps.) flowing to grid and anode is given by the well-known expression||

$$i = \frac{1{\cdot}47 \times 10^{-5} l}{b\beta^2}\left[\frac{V_a + \mu(V_g + v)}{1 + \mu}\right]^{\frac{3}{2}} \quad . \quad (5)$$

where l is the length of the cathode, V_a is the potential of the anode relative to the cathode, V_g is the potential of the grid relative to the cathode, v is a small voltage correction which takes into account the contact potential-

* See Reference (8).
† The total power dissipated in the anode is, of course, $P + \alpha P_c$, where α is the proportion of the cathode power (P_c) absorbed by the anode and may be as high as 0·8.

* See Reference (9).
† *Ibid.*, (10).
‡ *Ibid.*, (11).
§ *Ibid.*, (12).
|| *Ibid.*, (13).

difference between grid and cathode and the initial velocity of the electrons (a function of the cathode temperature), and

$$\beta = \log\frac{b}{c} - \frac{2}{5}\left(\log\frac{b}{c}\right)^2 + \frac{11}{120}\left(\log\frac{b}{c}\right)^3 - \ldots$$

b and c being the radii of grid and cathode respectively.

When the grid is sufficiently negative to prevent electrons passing from cathode to grid, i is the anode current, and the mutual conductance g_m is given by

$$g_m = \frac{\partial i}{\partial V_g} = \frac{3}{2}\left\{\frac{1\cdot 47 \times 10^{-5} \times l\mu[V_a + \mu(V_g + v)]^{\frac{1}{2}}}{b\beta^2(1+\mu)^{\frac{3}{2}}}\right\} \quad (6)$$

and the anode impedance is

$$r_a = \frac{\mu}{g_m} = \frac{2b\beta^2(1+\mu)^{\frac{3}{2}}}{3 \times 1\cdot 47 \times 10^{-5} l[V_a + \mu(V_g + v)]^{\frac{1}{2}}} \quad (7)$$

It therefore follows that, for a given value of μ, the impedance may be reduced and mutual conductance increased by increasing the length of the cathode and/or reducing $b\beta^2$.

In directly-heated filament valves a high mutual conductance and low impedance may be obtained by employing a long filament system, the upper limit being determined by the emission per unit length of filament necessary to ensure that the anode current is space-charge-limited, and by other factors which will be considered in a later part of this paper. In indirectly-heated cathode valves, where it is not possible to employ long cathodes, the mutual conductance is increased by reducing the grid-cathode clearance.

In high-amplification-factor triodes, the upper limit of mutual conductance is set by the minimum value to which it is possible to reduce the grid-cathode clearance without risk of excessive variations in characteristics, due to accidental variations in this parameter, and by the degree to which it is possible to control the contact potential-difference between grid and cathode, μv being comparable with V_a [equations (5) and (6)].

In low-impedance triodes for output stages of a receiver, the limiting factors are different. The contact potential-difference between grid and cathode is relatively unimportant, since V_a is large compared with μv. There is a mechanical limitation to the minimum size of the grid wires (ρ) which can be employed, and minimum values to which it is permissible to reduce grid-cathode and anode-grid spacings without risk of grid emission and excessive anode temperature. Further, it is not possible to reduce n indefinitely, since as the ratio of grid pitch ($1/n$) to grid-cathode clearance increases *Inselbildung* becomes more serious, and affects the shape of the anode-current/anode-voltage curve at high anode voltages. This reduces the efficiency of the valve by limiting the maximum undistorted output obtainable. Fig. 3, in which the mutual conductance at constant anode current is plotted against grid pitch, shows the effect of *Inselbildung* in some experimental valves. As mentioned earlier, this phenomenon is present to some extent in nearly all receiving valves; but in low-impedance valves, where unfortunately its effect is most serious, it is most marked, and the manufacture of an indirectly-heated-cathode power output triode is only possible by the use of extremely fine wires for the grid together with a very small clearance between the grid and anode.

The maximum theoretical efficiency (ratio of output watts to anode dissipation) of an ideal triode, having zero impedance, would be 50 per cent. In practice, owing to the limitations mentioned above, the maximum efficiency obtained—even with directly-heated cathode valves—is only about 25 per cent. By using a pair of valves in push-pull it is possible to increase the efficiency since the second-harmonic distortions of the two valves neutralize one another, and lower-impedance valves together with low load impedance can be employed. An efficiency of 40 per cent can in this way be obtained. The efficiency can be still further improved by allowing the grid potentials of the valves to become positive over part of each cycle. From the point of view of the valve itself, the fact that an electron current is flowing to the grid introduces new problems in manufacture.

Greater precautions are necessary in pumping the valve to ensure that the grid is really gas-free, as, otherwise, this gas will be liberated by electron bombardment when the grid is positive and will " poison " the cathode. Further, since the grid is hotter than in a valve operating with no grid current, primary electrons may be emitted; and, although the input circuit of the valve is designed to deliver power to the grid circuits, a large increase in grid emission would be serious.

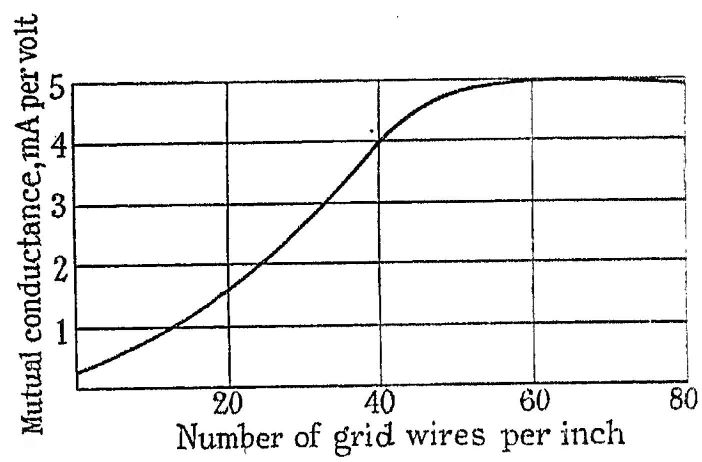


Fig. 3.—Effect of grid pitch on mutual conductance.
Cathode diameter 2·1 mm., grid diameter 3·3 mm., $E_g = 0$, $I_a = 8\cdot 0$ mA.

TETRODES

Expressions giving the various characteristics of tetrodes (and pentodes) in terms of electrode dimensions and potentials have been calculated for simple electrode systems, but in practice these are of even less value to the valve designer than the equations for the triode, owing to the complex design of the electrodes and the effect of secondary emission. It will, however, be obvious that since the anode is screened from the grid, and therefore from the cathode, its dimensions and potential will have little effect on the anode current and mutual conductance of the valve compared with cathode, grid, and screen dimensions, and it is the design of these electrodes which is most important in determining the characteristics.

Tetrode valves may be divided into two classes: (*a*) high-frequency amplifier and detector valves, and (*b*) low-frequency output valves.

(a) Screen-Grid Valves

The principal requirement in these valves is that the screen shall reduce the capacitance between anode and control grid to a very low value (0·001–0·01 $\mu\mu$F). In practice, this is achieved by making the screen from sheet metal surrounding the grid as far as possible, with apertures covered by very fine mesh opposite the region of the cathode-grid system from which electrons are escaping. The screen is usually provided with one or more skirts which extend to the walls of the bulb, so that the screening can be completed outside the valve. The anode is designed to have as small a surface as is possible without unduly increasing the space charge between screen and anode. Two designs of screen-grid valve are shown in Fig. 4.

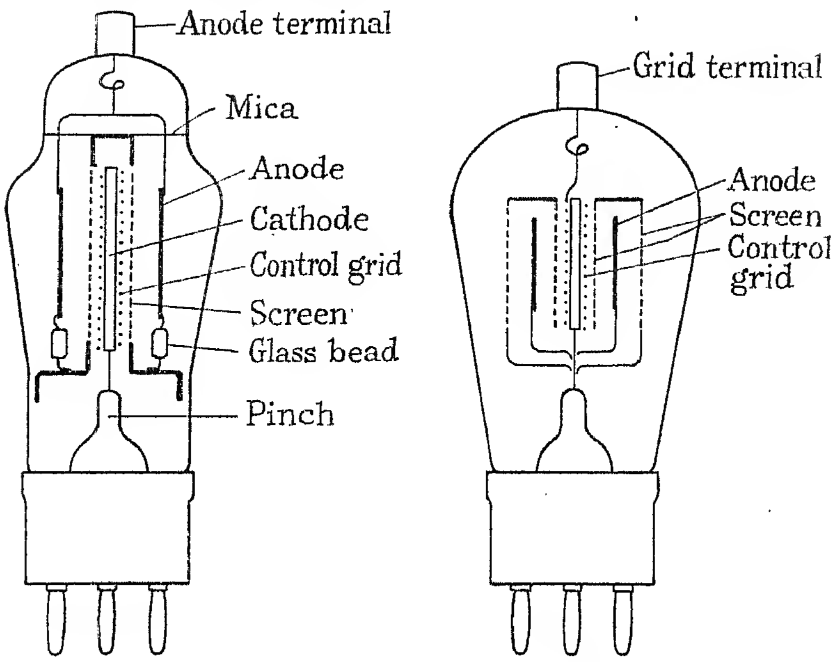


Fig. 4.—Screen-grid valves.

The general shape of the characteristic curves (Fig. 5) is well known. When the anode potential is lower than that of the screen, secondary electrons pass from anode to screen, thus reducing the anode current below, and increasing the screen current above, the values which they would have if secondary emission were absent. When the anode potential is above that of the screen, the secondary electrons flow from screen to anode, thus increasing the anode current and decreasing the screen current. With modern oxide-coated cathodes, screen and anode surface become contaminated with barium from the cathode (the actual layers having a complex BaO, O, Ba structure), which increases the secondary-emission coefficient considerably, and the phenomenon of a negative screen current (when the ratio of the number of secondary electrons flowing from screen to anode to the number of primary electrons from cathode to screen is greater than unity) is quite common. It will be noted that the higher the secondary emission from the screen, the higher the mutual conductance of the valve, which is in fact a secondary-electron multiplier. Unfortunately, the secondary emission is extremely difficult to control, and is dependent not only on the degree of contamination of the surface but also on its mechanical nature.

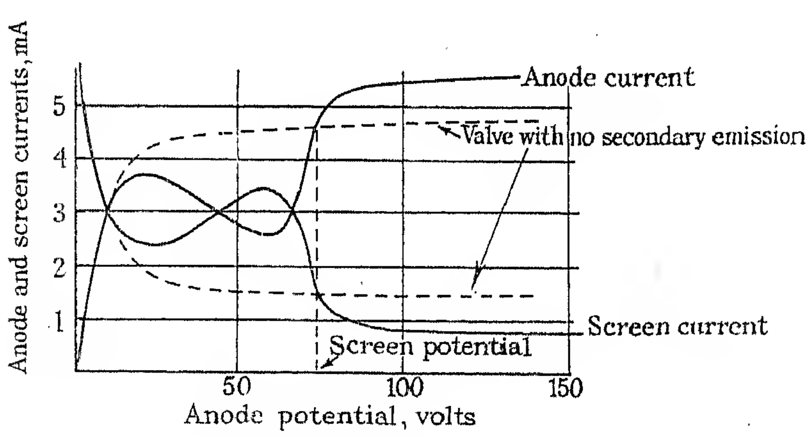


Fig. 5.—Screen-grid valve characteristics.

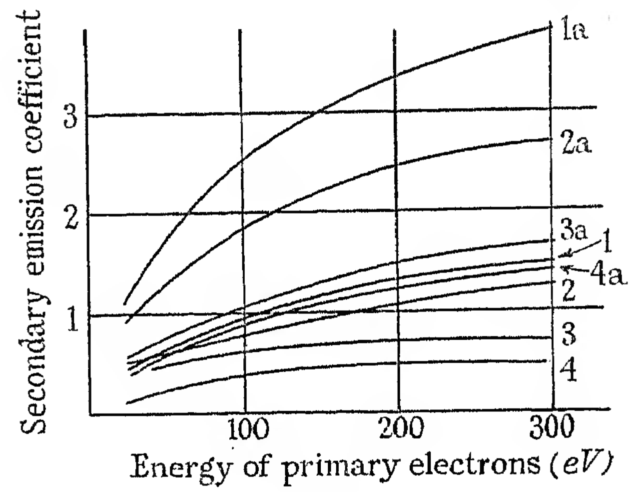


Fig. 6

1. Clean molybdenum.
1*a*. Barium on molybdenum.
2. Clean graphite (aquadag).
2*a*. Barium on graphite (aquadag).
3. Clean carbonized nickel.
3*a*. Barium on carbonized nickel.
4. Clean lampblack.
4*a*. Barium on lampblack.

The secondary emission of clean and contaminated surfaces has been studied in the G.E.C. Laboratories, and Fig. 6 shows the effect of depositing barium from a barium-oxide cathode on various substances. The difference between colloidal graphite (aquadag) and lampblack is particularly interesting, the secondary emission of the former being approximately the same as for a metal, whereas the value for lampblack is only about one-third that of a metal. Screen-grid valves have been made with carbonized screens in an attempt to reduce the spread in characteristics between valves, and during life. Another method of reducing the

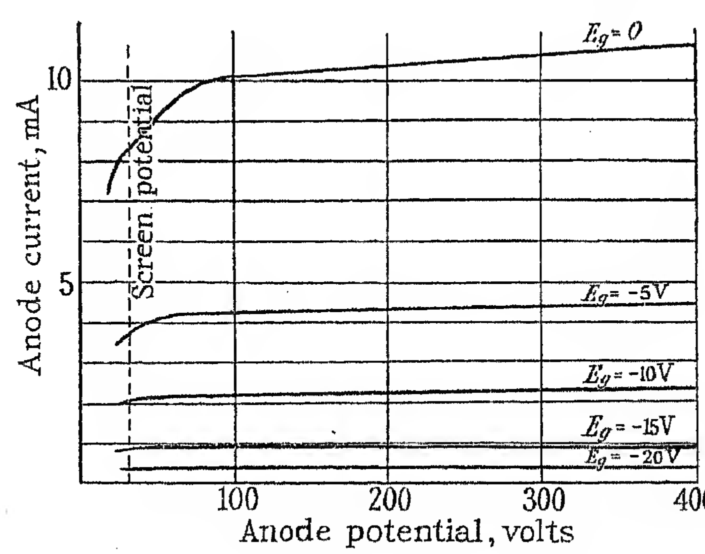


Fig. 7.—Variable-mu screen-grid valve designed for screen at 30 volts.

secondary emission is to lower the screen potential, the grid-screen clearance being reduced in order to maintain the characteristics. Anode-current curves of a screen-grid valve in which the screen was designed to operate at 30 volts are shown in Fig. 7.

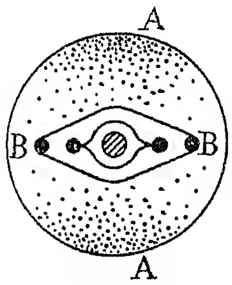


Fig. 8.—Space-charge distribution between screen and anode of tetrode (at low anode voltage).

(b) Low-Frequency Tetrodes

In low-frequency tetrode valves the capacitance between anode and grid is less important than in high-frequency valves, and the screen can be a much more open structure. The secondary emission from the

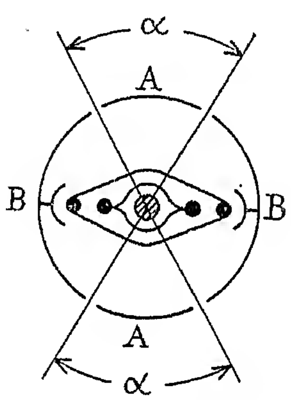


Fig. 9.—Tetrode with earthed plates to suppress secondary emission.

screen is therefore less. For a tetrode to be an efficient output valve, the secondary emission between anode and screen must be suppressed. This can be done in either or both of two ways: (*a*) by so designing the anode, or by making the distance between anode and screen

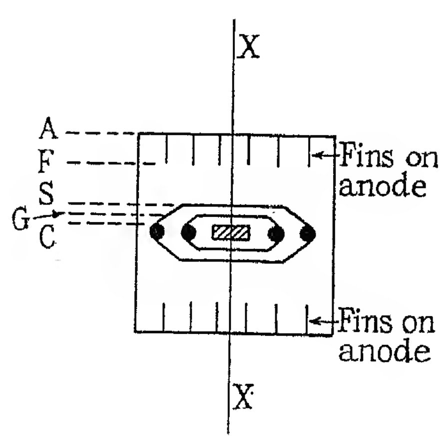


Fig. 10.—Tetrode with fins on anode to suppress secondary emission.

so large, that the space charge produces a potential minimum between anode and screen: and/or (*b*) by making the distance between screen and grid small, and the screen an open structure so that a potential minimum is produced outside the screen by the grid, which is always at a negative or zero potential. Most of the secondary electrons possess low initial velocities, so that provided the space-potential minimum is a few volts lower than that of the screen or anode (whichever has the lower potential) secondary electrons will return

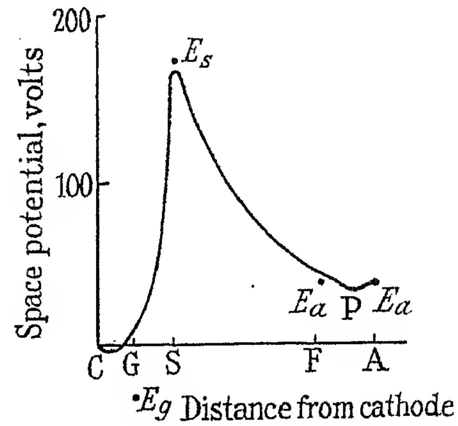


Fig. 11.—Potential distribution in tetrode with fins on anode (at low anode voltage).

to the electrode from which they emanate. In practice, unless the distance between anode and screen is very large, since the electrodes are not axially symmetrical, the density of electrons in the neighbourhood of the support wires (see Fig. 8) is small even when the anode current is high, so that although there may be a potential minimum in the region A there is no potential minimum at B and secondary electrons can pass freely between anode and screen. Bull* has suggested a method of overcoming this difficulty by arranging the electrodes in the way indicated diagrammatically in Fig. 9. The anode AA is in the form of two segments of a cylinder, and BB are two additional electrodes operated at zero or negative potential to concentrate the electron stream between the boundaries enclosing the angle α. An alternative design which has been used in tetrodes designed to operate at relatively low anode and screen

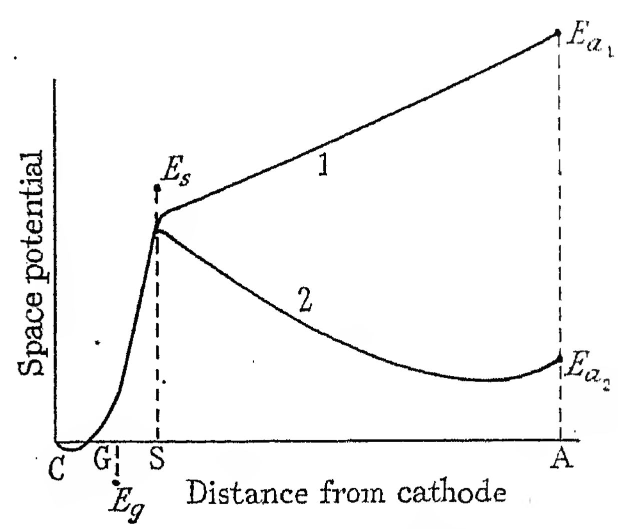


Fig. 12.—Potential distribution in tetrode with small clearance between grid and screen.

1. Anode potential higher than screen potential.
2. Anode potential lower than screen potential.

potentials is shown in Fig. 10, fins F being provided inside the anode. The potential varies from cathode to anode along the plane XX in the way indicated in Fig. 11, and most of the secondary electrons from the

* See Reference (14).

anode surface will be prevented from escaping by the potential minimum at P, or will be trapped by the fins.

It will be noticed that condition (*b*) mentioned above necessitates an increase in grid-anode capacitance, but this increase, if small, is not a serious disadvantage in output valves. The potential variation from cathode to anode is illustrated in Fig. 12; and the characteristics of a valve designed so that conditions (*a*) and (*b*) were satisfied are shown in Fig. 13.

The complete suppression of secondary emission in a tetrode is not an easy matter, particularly in valves designed to operate at high anode and screen potentials, and by far the most common method of suppressing the secondary electrons is by the inclusion of a suppressor grid—as in the pentode valve.

PENTODE VALVES

Pentode valves may be divided into two main classes: high-frequency valves, in which the screening between anode and grid is important; and low-frequency valves, in which the principal requirement is high output efficiency. The latter class will be considered first.

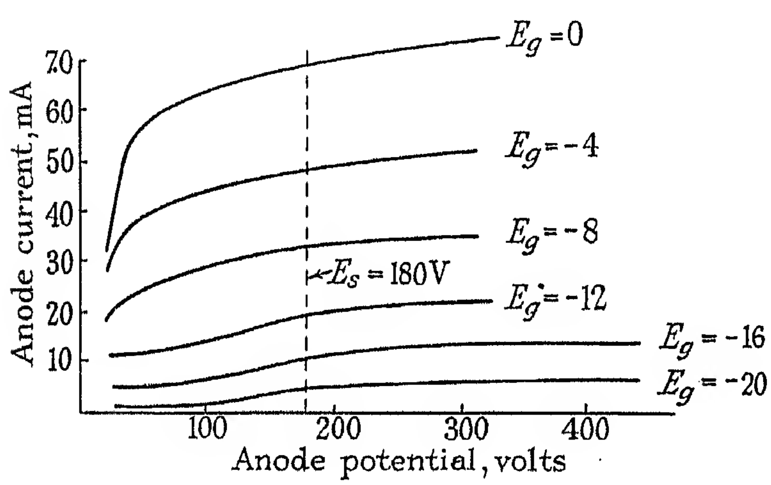


Fig. 13.—Characteristics of tetrode with large anode-screen and small grid-screen clearances.

(a) Output Pentodes

The general shape of the anode-current/anode-voltage curve of an output pentode is well known, and is shown in Fig. 14, the secondary emission " kink " in the curve which is characteristic of most tetrodes having been removed by the suppressor grid. The anode and suppressor-grid potentials have little effect on the field near the cathode surface, and therefore on the anode current and mutual conductance, which are functions of the cathode-grid-screen design and potentials in the same way as, in a triode, these characteristics depend on the cathode-grid-anode design and potentials. The amplification factor of the valve is, of course, the product of the amplification factors of the anode-grid, anode-screen, and anode-suppressor grid systems. The design of the suppressor grid, which can only be decided by trial for any particular valve, is most important in determining the shape of the " knee " of the curve. If the pitch of the suppressor-grid spiral is too small, the minimum space potential in the neighbourhood of the suppressor grid will have a slightly negative value relative to the cathode when the anode potential is low, and primary electrons will fail to reach the anode, with the result that the anode-current characteristic will be as shown in Fig. 15, curve (*a*). If, on the other hand, the pitch of the suppressor grid is too large, then at low anode potentials some of the secondary electrons will reach the screen, and the anode-current characteristic will be as

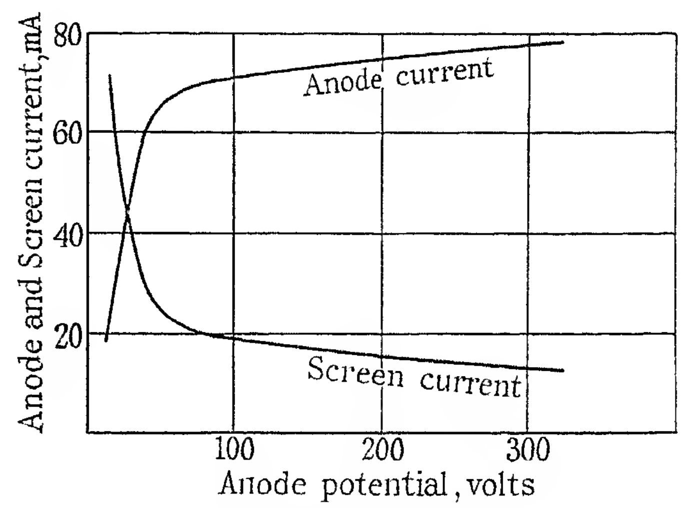


Fig. 14.—Characteristics of pentode.

in Fig. 15, curve (*b*). In either case it will be obvious that the maximum undistorted output will be limited, and, in designing the suppressor grid, its optimum dimensions must be determined by trial.

The pitch of the screen-grid spiral also affects the shape of the characteristics, and here a compromise must be effected between an open structure which allows the potential of the anode to affect the field near the cathode, thus reducing the anode impedance and limiting the output [Fig. 15, curve (*c*)], and a close structure which will result in excessive screen current. The pitch of the screen-grid also affects the " knee " of the anode-current/anode-voltage curve in another way. The dispersion of the electron paths through the screen-grid depends on the pitch of this grid,* being smallest when the pitch is small. It will be obvious that, the smaller this dispersion, the lower will be the anode voltage necessary to draw all the electrons passing through the

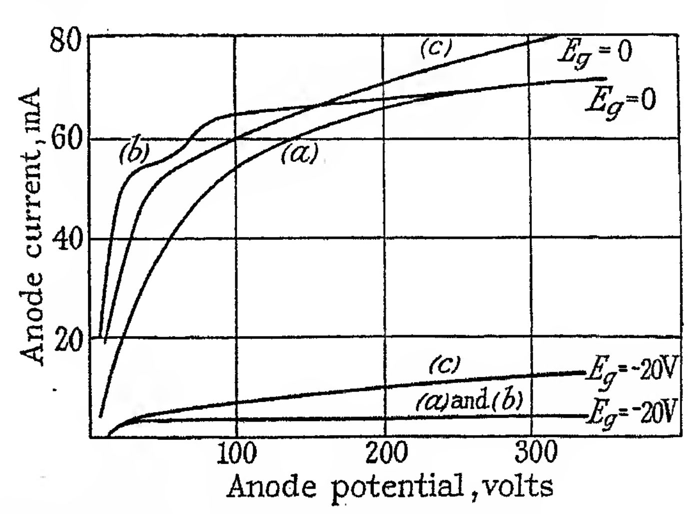


Fig. 15.—Effects of modifications to design of suppressor-grid and screen-grid in a pentode.

screen to the anode, and consequently the better the " knee " to the characteristic curve.

It might be expected at first sight that the limitations already mentioned in connection with indirectly-heated

* See Reference (15).

cathode triodes would also be encountered in the design of output pentodes. This, however, is not so; for the μ value of the grid-screen system need not be very low, since the output efficiency is less dependent on this factor than it is on the anode impedance of a triode. Further, *Inselbildung*, which is a function of the anode potential in a triode, is independent of the anode potential in a pentode.

(b) High-Frequency Pentodes

The principal difference between high- and low-frequency pentodes is, as in the case of tetrodes, in the anode-grid capacitance. A high anode impedance is usually desirable in the high-frequency pentode, and this characteristic is fortunately complementary to a high degree of screening.

For convenience in manufacture, and also in order to keep the screen current as low as possible, the screen is usually made in the form of a close-wound grid, and the screening at the ends of the electrodes is completed by a skirt or skirts attached to the suppressor grid.

Although not usually designed for use with a control voltage on the suppressor grid, the high-frequency pentode can be used in this manner.* As the potential of the suppressor grid is made more negative, the anode current is reduced and screen current increased, and at the same time the anode impedance is reduced. With a suppressor grid having a very open pitch, however, the control on the anode current by this grid is poor, and it is natural that grids having a closer pitch should have been employed to improve this control. This led to the development of hexodes, heptodes, and octodes, which are designed specifically for the control of the anode current by two separate grids. These will now be described, and the action of the second control grid will be briefly considered.

HEXODES, HEPTODES, AND OCTODES

These may be divided into two classes, depending on the particular use for which they are designed rather than on a fundamental difference of principle.

The first class, including hexodes and certain heptodes, consists essentially of a high-frequency pentode in which the pitch of the third grid is reduced in order to obtain a good control of the electron stream, and to which a screen is added between this grid and the anode to overcome the variation in anode impedance mentioned above. The heptodes in this class have, in addition, a suppressor grid between this second screen and the anode. The main use of these valves is for frequency-changing in superheterodyne receivers, the signal voltage being applied to the inner control grid (which usually has a variable-mu characteristic) and the oscillator voltage (derived from a separate source) being applied to the outer control grid.

The design of the cathode, control grid, and screen section is essentially the same as in a high-frequency pentode. The action of the second control grid, however, is different from that of the grid of a triode. Whereas in the triode space charge is an essential intermediary in the relationship between anode current and grid potential, it is the potential distribution in the plane of the outer control grid which mainly determines this relationship in the case of the hexode (or heptode). The electrons leave the inner screen with a high velocity, and whether or not a particular electron or group of electrons will reach the anode (and outer screen) or return to the inner screen depends on the position of

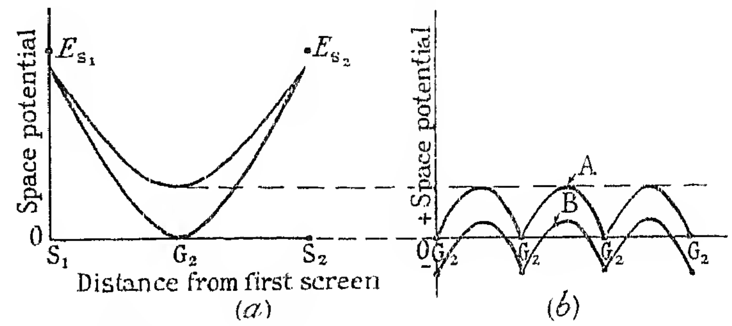


Fig. 16.—Potential distribution in hexode.

(a) Potential distribution between the two screens.
(b) Potential distribution in plane of second control grid.
A. Control-grid potential zero.
B. Control-grid potential negative.

the electron paths relative to the second control-grid wires, the space-potential distribution in the neighbourhood of this grid, the deflection of the electron paths by the inner screen, and the initial velocity of the electrons as they leave the cathode. The calculation of the dimensions of the second control grid from theoretical considerations is not in practice possible, but a general picture of the action of the grid can be obtained from Fig. 16, which represents the potential distribution (a) between the two screens of a hexode, and also (b) in the plane of the second control grid. The maximum anode current will be obtained with approximately zero potential on the control grid, space charge being small; and the anode current, when this grid is at a negative potential, will depend on the effective potential in the grid plane. This latter is given by Schottky's formula,* namely

$$V_{eff.} = \frac{DV_a + V_g + RV_s}{1 + D + R}$$

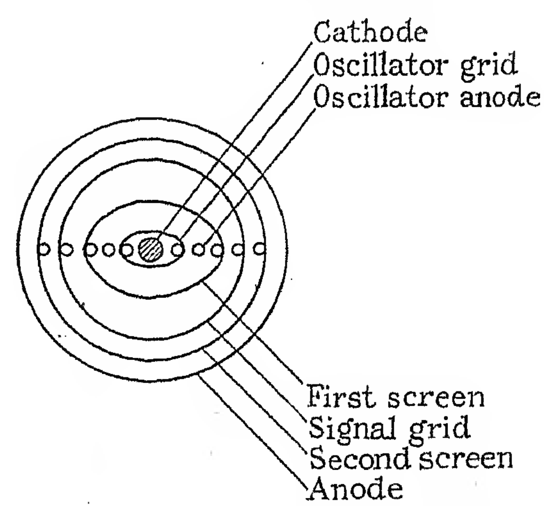


Fig. 17.—Electrode arrangement in heptode.

where D is the *Durchgriff*† of the outer electrodes (anode, outer screen, and suppressor grid, in a heptode) through the grid, and R is the *Ruckgriff*† of the inner electrodes through the grid. It is clear, therefore, that close spacing between these electrodes and high voltages tend to lower the control of the second control grid.

* See Reference (16).

* See Reference (2).
† "Durchgriff" and "Ruckgriff" are the reciprocals of the amplification factors of the grid-outer screen and grid-inner screen systems respectively.

The second class of heptodes, together with octodes, differ from the above chiefly in that they contain an additional electrode at a positive potential between the inner control grid and screen, the inner triode system being used as an oscillator to modulate the electron stream. The outer control grid in these valves, which usually has a variable-mu characteristic, is used for the signal input. The control action of the additional electrode (triode anode) on the electron stream must be less than that of the inner grid, as otherwise the resultant modulation of the electron stream will be low (in the limiting case, if the control of the oscillator electrodes were equal, equal and opposite voltages would leave the electron stream constant). For this reason, and also to reduce the interaction between the second control grid and the oscillator, the oscillator anode is usually in the form of two wires parallel to the cathode which may even be placed between the support wires of the inner grid and screen (Fig. 17). In this case, the oscillator anode current is mainly the result of secondary emission from the screen.

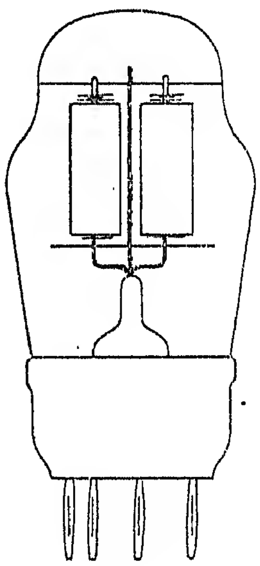


Fig. 18.—Double pentode.

MULTIPLE VALVES

The design and manufacture of multiple valves does not introduce any fundamentally new principles, such valves being made mainly for the convenience of set manufacturers, and it will only be necessary to refer to these types briefly.

Double output valves (triodes and pentodes) for push-pull operation with or without positive grid drive merely consist of two separate valve-assemblies mounted side by side on a single pinch (Fig. 18). Precautions are necessary in the design of these types to ensure that there is no mutual control between the two electrode systems, such as would occur if the anodes were made of mesh or if electrons escaped from the ends of the electrodes, and that the temperatures of the electrodes do not become excessive owing to heat radiated from one system to the other.

In double diode triodes, the anodes of diodes, which only require a small total emission to satisfy their characteristics, are usually mounted at the end of the cathode nearer the pinch, and the grid of the triode, screened from the diode anodes, is connected to a cap at the top of the bulb (Fig. 19).

The triode hexode, which is used as a combined oscillator and frequency-changer, is made in a similar manner, the triode being assembled on the lower end, and the hexode on the upper end, of a common cathode. The hexode signal-control grid (nearest the cathode) is connected to the top cap, and the triode grid is connected internally to the second control grid of the hexode (Fig. 20).

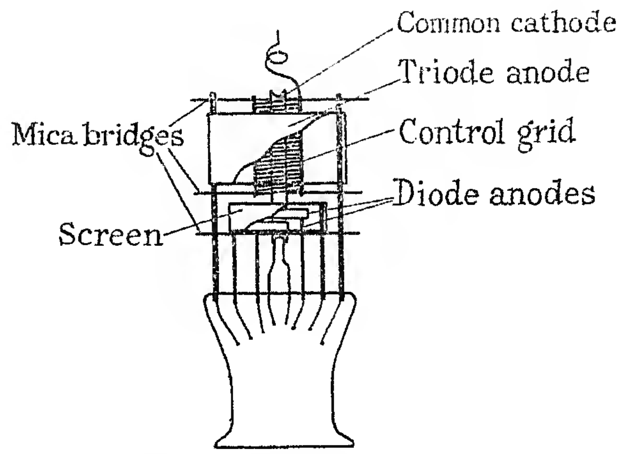


Fig. 19.—Double diode triode.

FACTORS AFFECTING CHARACTERISTICS

In addition to the development of special types of valves and to improvements in the characteristics, a continuous effort has been and is being made by valve manufacturers towards reducing, in any given valve type, deviations from the mean value of the characteristics; since with greater uniformity in the product the set manufacturer is able to use more efficient circuits. It may, at first sight, seem rather surprising to the user of valves that the spread in characteristics from valve to valve is, even with the utmost precautions in manufacture, quite large: $\pm$ 20 per cent and in some cases $\pm$ 40 per cent on such characteristics as anode current and mutual conductance being the smallest limits to which it is at present possible to work economically.

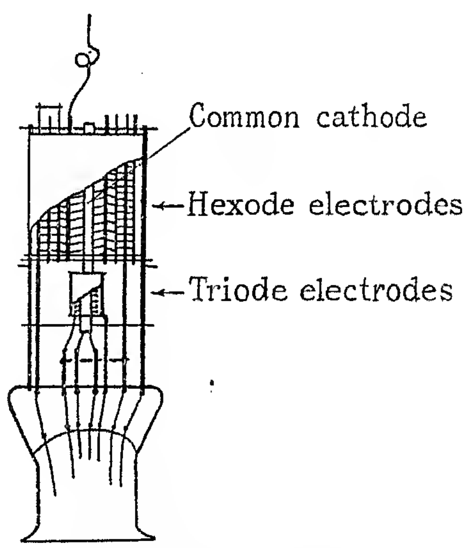


Fig. 20.—Triode hexode.

From the remarks made earlier in the paper it will be seen that the factors which affect the characteristics of a valve are the mechanical dimensions and chemical

properties of the surfaces of the electrodes. With the small distances between electrodes which are employed to obtain the high efficiency of the modern valve, and lack of continuity in the production of any given type, uniformity in these two factors becomes increasingly difficult.

(a) Mechanical Variations

A fairly accurate idea of the effects of small variations in the mechanical dimensions of the various electrodes can be obtained from a consideration of the approximate expressions given earlier in this paper and elsewhere for the characteristics of the valve. Thus, to take the simplest case of a triode, the effect of variations in the parameters a, b, c, ρ, n, l, on the characteristics μ, i, g, R can be obtained from equations (4), (5), (6), and (7) by logarithmic differentiation of these functions with respect to the various parameters. The expressions, which are readily deduced, are rather complex, and the authors will therefore content themselves with giving in Table 1 one of the results of calculations which have

Table 1

Triode valve: $a=0\cdot617$ cm., $b=0\cdot187$ cm., $c=0\cdot099$ cm., $\rho=0\cdot0055$ cm., $n=15\cdot75$ per cm., $l=3\cdot5$ cm., $V_a=100$ volts, $V_g=0$, $v=0\cdot83$ volt.

	$\delta a/a$	$\delta b/b$	$\delta c/c$	$\delta\rho/\rho$	$\delta n/n$	$\delta l/l$
$\delta\mu/\mu$	0·84	0·16	0	1·23	2·23	0
$\delta i/i$	−0·90	−3·59	2·42	−1·32	−2·38	1
$\delta g/g$	−0·28	−3·47	2·42	−0·40	−0·73	1
$\delta R/R$	1·12	3·63	−2·42	1·64	2·96	−1

been made for a particular high-impedance triode. This table gives the coefficients B in the expression

$$\frac{\delta A}{A} = B\frac{\delta C}{C}$$

where A is one of the characteristics μ, i, g, R; and C is one of the parameters a, b, c, ρ, n, l.

It will be seen that an error of 1 per cent in the radius of the cathode, for example (representing an absolute error of 0·001 cm.), will introduce an error of 2·42 per cent in the value of the anode current, mutual conductance, and impedance. If small errors in more than one parameter exist, then the effects are, of course, additive; so that if a, b, ρ, n are 1 per cent too large and c and l 1 per cent too small, the total deviation in anode current from its correct value will be as much as 11 per cent. In practice, the tolerances to which it is possible to manufacture components on a large scale economically for a valve such as that cited in Table 1 are: cathode diameter $\pm$ 1 per cent (including coating), grid diameter $\pm$ 1 per cent, grid pitch (mean) $\pm$ 1 per cent, grid-wire diameter $\pm$ 1½ per cent, anode diameter $\pm$ 2 per cent; and although it is extremely improbable that all the maximum permissible errors will occur at the same time in any given valve, a total variation in characteristics of $\pm$ 5 to $\pm$ 10 per cent, due to mechanical variations alone, will exist in quite an appreciable percentage of valves. It will readily be seen that any improvement in the mutual conductance effected by reducing the grid diameter will increase the values of the coefficient B in the expression

$$\frac{\delta A}{A} = B\frac{\delta C}{C}$$

and make the task of manufacturing a uniform product more difficult. Mechanical shock or strain in the materials which might result in slight distortion of the electrodes will also seriously affect the characteristics.

In valves having more than three electrodes, the possibility of variations in characteristics will be greater, although in these cases also the dimensions of the cathode and control grid are generally the most important factors.

(b) Chemical Variations

The factors, other than mechanical, which affect the characteristics are the degree of activation of the cathode along its length, depending on the temperature distribution (which is discussed in another part of this paper), the contact potential difference-between cathode and grid, and secondary emission in tetrodes and other types in which no auxiliary grid is used to suppress secondary currents. The effect of variations in grid-cathode contact-potential is, as already stated, most serious in valves with high amplification factor and high mutual conductance, and is indeed the biggest single cause of variation in characteristics in these types. For example, in a valve designed to operate with an anode current of 6 mA with a mutual conductance of 6 mA per volt a change of 0·1 volt in the grid-cathode contact potential-difference will result in a deviation of 10 per cent in the anode current, and over 3 per cent in the mutual conductance. In low-amplification-factor valves in which the ratio of mutual conductance to anode current is small, the effect of variations in grid-cathode contact potential-difference is, of course, much smaller and may be negligible; as, for example, in a valve such as a 100-watt output valve operating at 100 mA anode current with a mutual conductance of 3·9 (Fig. 21).

As has been mentioned earlier, the contact potential-difference between anode and cathode in a detector diode, or cathode and grid of a triode, tetrode, pentode, etc., is determined by the materials used for the electrodes, the physical nature of the surface, and the contamination (metallic or gaseous) on the surface. Even when a close control is exercised on all the materials and operations during manufacture, it is not possible economically to control the variations in grid contact-potential to within closer limits than $\pm$ 0·2 volt of a mean value. A particular difficulty arises in the case of such valves as double diode triodes where for certain circuit requirements it is necessary to keep the contact potential-difference between cathode and diode anodes approximately equal to that between cathode and triode grid, so that the diode anode current shall start at the same negative bias value as that at which grid current starts. The difficulty arises owing to the fact that the grid-wire material is usually different from the diode-anode material, and also that the evaporation of barium

from the ends of the cathode on to the diode anodes is less rapid than from the centre of the cathode on to the grid. Special care is necessary in devising activating processes which will satisfy the above requirement without de-activating the cathode, and it is often necessary to subject such valves to very long ageing treatment in order to establish stable characteristics.

The control of secondary emission is equally difficult, and depends on the same factors as does contact potential. It has in fact been shown in the G.E.C. Laboratories* that the secondary emission from a contaminated surface is closely related to its contact potential and work function. Variations of $\pm$ 50 per cent in the value of secondary current from the screen to the anode of a screen-grid valve are quite common, and will introduce deviations from the mean value of anode current of 15 to 20 per cent, while the value of the screen current may vary between positive and negative values.

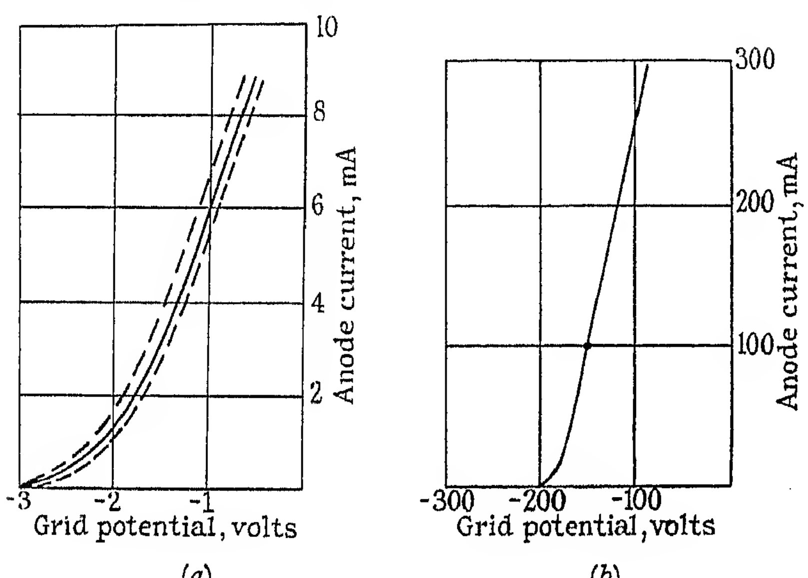


Fig. 21

(a) High-impedance triode, showing large effect of contact-potential variation.

(b) Low-impedance triode, showing negligible effect of contact-potential variation.

(c) Negative Grid Current and Input Impedance

The main causes of negative grid current when the grid is at a negative potential with respect to the cathode are: (i) Leakage across insulators. (ii) Positive-ion current to the grid due to poor vacuum. (iii) Electron current from the grid (grid emission). The maximum permissible value of the total grid current due to these causes varies, according to the purpose for which the valve is used and according to the value of the resistances which may be included in the grid circuit, between 10^{-8} and 5×10^{-6} amp.

(i) Leakage.

Little difficulty is experienced in obtaining electrode spacing insulators having a sufficiently high resistance (of the order 10^{10} ohms) even with the small distances between electrode support wires; but films of metal (e.g. barium) deposited on the insulator surfaces during pumping and subsequently, may reduce the insulation considerably. When mica is used, it is usual to roughen the surface by covering it with a thin layer of magnesium oxide, so that the metallic deposits do not form continuous films between electrodes. Another possible source of leakage between electrodes is the glass pinch, if its temperature rises and electrolysis occurs. The

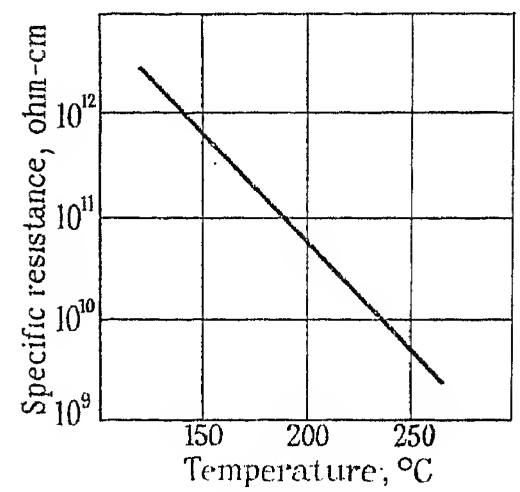


Fig. 22.—Specific resistance of glass used for valve pinches.

material used for valve pinches is usually a lead glass having high insulating properties (Fig. 22), and in practice leakage currents are negligible if the temperature is below 200° C. In power output valves and power rectifiers, special precautions may be necessary to ensure that this temperature is not exceeded. Most of the heat received by the pinch is conducted to it along the electrode support wires, and the substitution of wires of a metal with low thermal conductivity, such as nickel-chromium or nickel-iron alloys instead of nickel, reduces the temperature of the pinch considerably. To give one example, in an output pentode in which the temperature of the pinch was regarded as being dangerously high (205° C.) with nickel support wires to the anode, the substitution of nichrome wires reduced its temperature to 158° C. In the "ring seal," shown in Fig. 23, which has been used for several types of small valves, the glass is at a very low temperature, and the lead-in wires are separated from one another by greater distances than are possible in the usual type of flat pinch. Leakage currents through the glass are therefore negligible.

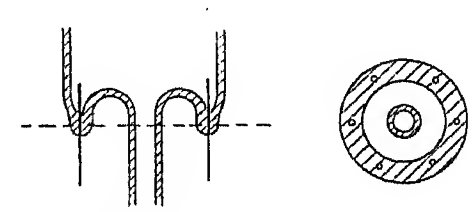


Fig. 23.—Glass ring seal.

(ii) Positive-ion current.

The gas pressure which will produce a given positive-ion current to the grid of a valve depends on the nature of the gas, the magnitude of the electron currents, the potentials of the electrodes, and the electrode design, and is therefore different for different types of valve. Valves in which the control grid is not adjacent to the cathode, such as the heptode oscillator-detector, are more sensitive to gas than triodes, tetrodes, and pentodes.

* See Reference (17).

Measurements made on representative types of valves have shown that the maximum permissible pressure which may exist without causing excessive grid current is of the order 10^{-5} mm. of mercury. Although the pumps used for exhausting valves in mass production are not capable of reducing the pressure to less than 10^{-3} to 10^{-4} mm. of mercury, the average pressure in modern valves using efficient getters (such as barium) is about 10^{-7} mm. or in some cases as low as 10^{-8} mm. of mercury.

(iii) Grid emission.

In power output valves and in indirectly-heated cathode valves, in which the grid-cathode clearance is small, electron emission from the grid is difficult to prevent. Many attempts have been made to reduce grid emission by treatment of the surface of the grid wires, such as plating with copper or silver. These metals can dissolve barium deposited on them, leaving a low barium concentration on the surface, which has a relatively high work function. Experiments have shown, however, that little difficulty would be experienced if barium metal alone were deposited on the clean grid surface, and that it would be possible for a grid contaminated in this way to operate at a temperature as high as 400° C. without risk of excessive emission. Barium oxide on the grid surface, however, may cause serious grid emission at temperatures as low as 320° C., and the main difficulty arises owing to the fact that the grid surface may oxidize during pumping when the barium-strontium carbonates are being decomposed, and a barium-on-barium-oxide layer then results from the subsequent deposition of barium on the oxidized grid surface. Although plating the grid with silver or copper is effective in reducing the average value of grid emission in any type of valve, it is not a certain cure, and the authors have found that in large-scale production a small percentage of valves with excessive grid current is produced. Further, the volatilization of the metal or the oxide of the metal deposited on the grid often "poisons" the cathode emission.

The only sure method at present known of preventing emission from the grid of a valve is to keep the grid temperature below 320° C., and to do this when the grid wires may be less than 0·5 mm. from a cathode at 770° C. is not easy. Grid support wires made of a metal with high thermal conductivity, e.g. copper, are employed in some types of valves, often with radiating fins welded to the end of the grid (a modification which unfortunately increases the grid capacitance and makes screening more difficult). The thermal conductivity of the grid-winding wire material is also an important factor in this connection, as in the fine wires used there may be a considerable temperature gradient between the part of the grid nearest the cathode and the support wires. Some alloys which valve manufacturers would like to use (owing to their mechanical properties and low cost) have a very much lower thermal conductivity than molybdenum, and for this reason cannot be employed in grids adjacent to the cathode. The substitution of such alloys would increase the temperature of the hottest part of the grid by as much as 30 deg. C. and seriously increase the risk of grid emission.

Anodes and screens with carbonized surfaces or made from mesh instead of sheet metal are also used to prevent the grid from becoming overheated by radiation reflected from their inside surface. The temperature reduction effected in this way may be as much as 100 deg. C., and there are in fact few indirectly-heated valves made to-day in which this precaution is not necessary.

In addition to the three main causes of grid current mentioned above, there are several other contributory causes such as positive-ion emission from the cathode, and photo-emission from the grid. The values of these currents are, however, extremely small, and their elimination is only of importance in valves designed for special purposes, such as electrometer triodes and tetrodes, in which grid currents as low as 10^{-17} amp. are obtained.*

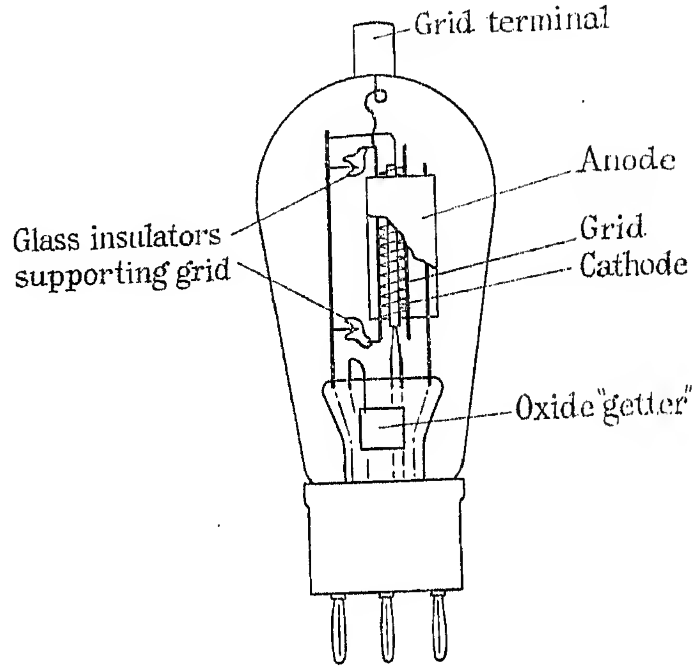


Fig. 24.—Triode for valve voltmeter.

During the past few years, the improvements in the efficiency of tuned circuits have necessitated a corresponding improvement in the high-frequency impedance between the grid and other electrodes of valves for use at radio frequencies. Circuits with an impedance of 0·5 megohm at 1 000–1 500 kilocycles per sec. are now quite common, and in order that the valve shall not seriously load such a circuit, its impedance must exceed 3 megohms. The valve base and socket are here the main limiting factors, and it is now becoming more usual to design valves for radio-frequency purposes with the grid lead taken to a cap on the top of the valve rather than to a pin in the base. When a still higher grid impedance is required, as in the case of valves for use as valve voltmeters at radio frequencies, specially-designed insulators for the grid are substituted for the usual mica bridge. A high-frequency voltmeter valve which has an impedance of more than 20 megohms at 1 200 kc is shown in Fig. 24.

(d) Bulb Charges

One other factor which may seriously affect the characteristics of a valve must be mentioned. This is secondary emission from the walls of the glass envelope.

* See References (18), (19).

It is well known that an insulated electrode in a thermionic valve can under certain conditions assume either of two stable potentials. If the electrode is initially at cathode potential or at any positive potential below that at which the number of secondary electrons emitted per primary is unity, then the electrode will collect

Fig. 25.—Output wave-form showing "buzz" effect.

electrons from the cathode until its potential has fallen to a small negative value $-V_1$ at which equilibrium is established between the rate of arrival of electrons having initial velocities greater than $\sqrt{(2V_1e/m)}$ (e and m being the charge and mass of the electron) and the leakage current between the cathode and free electrode. If, on the other hand, the initial positive potential of the free electrode is greater than the value V_c at which the ratio of secondary to primary electrons is unity, and the anode potential V_a is also higher than V_c, then the free electrode will assume a final equilibrium potential V_2 at which the secondary current from the free electrode to the anode is equal to the primary current from the cathode to the free electrode. The value of V_2 will depend on the secondary-emission coefficient at V_2 and the space charge in the neighbourhood of the free electrode.

The internal surface of a glass bulb, particularly if this is coated with a film of an electropositive metal such as barium, behaves in exactly the same way, and the characteristics of the valve will be modified according

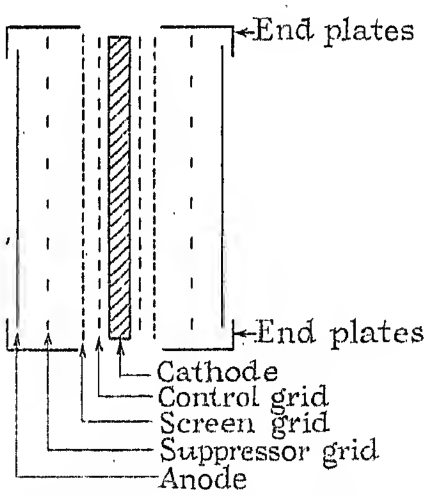


Fig. 26.—A method of preventing secondary emission from bulb.

to whether the surface is at the potential $-V_1$ or $+V_2$ since the potential distribution in the space inside the envelope will be different in the two cases.

The effect was observed in screen-grid valves several years ago, when it was found that the anode impedance fell to one-third its normal value if the bulb was raised initially to a high positive potential, or if the bulb surface became momentarily charged by electrostatic induction on applying a positive potential to the anode. The initial flow of electrons passing through the screen reached the bulb, secondary electrons were emitted, and a high bulb potential was maintained which reduced the valve impedance. Valves in which the envelope had been metallized externally did not exhibit the phenomenon since the metallic coating at earth potential prevented the inside surface of the bulb from acquiring a high positive potential.

More recently, a curious distortion of the output-current wave-form (Fig. 25) has been observed in some output pentode valves. This is known as the "buzz" or "S" effect, and is due to the induction of charges on the bulb which then emits secondary electrons when the anode potential swings above a critical value. In a power valve, it is not possible to metallize the outside surface of the bulb, as this would increase the temperature of the bulb and electrodes considerably, and shorten the life of the valve. One method of overcoming the difficulty is to arrange earthed screens at the ends of the electrode system, as shown in Fig. 26, so that no electrons from the cathode can reach the bulb. A simpler method which is effective in most cases is to coat the inside of the bulb with a material such as lampblack which has a low secondary-emission coefficient.

Table 2

	Valve type		
	Triode	Output pentode	Output pentode (air-cooled anode)
	°C.	°C.	°C.
Heater ..	1 150	1 150	1 150
Cathode ..	770	770	770
No. 1 grid ..	300	315	325
No. 2 grid ..	—	410	417
No. 3 grid ..	—	260	275
Anode ..	420	445	145

PROPERTIES OF MATERIALS, AND MANUFACTURE OF COMPONENTS

From what has already been said, it will be evident that a very close control must be kept of the mechanical properties of materials used for components. The manufacturer is limited in his choice of metals from which to make electrodes to those which possess high melting-points, and which have low vapour pressures even at temperatures as high as 1 000°–1 100° C., the temperature reached by the electrodes during pumping.

The operating temperatures of the electrodes vary according to the type of valve; Table 2, giving the results of measurements taken under operating conditions for a high-impedance triode and two output pentodes, is typical.

Nickel is usually employed as the anode material and for electrode support wires, but is not sufficiently rigid for the winding wires of grids. The diameter of these must, for reasons already stated, be as small as possible, and molybdenum, alloys containing molybdenum, or —for some purposes—nickel-manganese alloys, are used. All these metals are readily obtained free from undesir-

able impurities, are easily worked, and do not tarnish on exposure to the atmosphere, which in a valve factory may be extremely hot and humid. Iron is sometimes used as an anode material for screen-grid valves in which the anode is in the form of two plates, since it can be heated, during pumping, by hysteresis due to the magnetic field of the eddy-current heating coil.

Electrodes such as anodes and screens which are made wholly or in part from sheet metal are pressed into the required shape, and precautions must be taken to prevent distortion due to strain in the metal when it is heated in the valve.

The manufacture of grids, which at one time was an extremely laborious process, is now carried out on special machines capable of winding as many as 200–1 000 grids per hour, depending on the grid pitch. Fig. 27 shows a photograph of part of one of these machines. Fig. 28 shows rather more clearly the action of the machine. The support wires S are fed into grooves on the rotating mandrel M, and the winding wire G is wound into notches cut in the support wires by the fixed cutting-wheel C. The winding wire is fixed in position in the notches by a swaging wheel H which hammers the metal of the support wire over the winding wire. The earlier practice of welding is thus eliminated. The grids are wound in lengths of about 60 cm. and subsequently cut into the required lengths, and if necessary stretched or pressed to their final shape. By the operation of a cam on the machine a gap or gaps can be introduced in the winding of grids which are required to give a variable-mu characteristic.

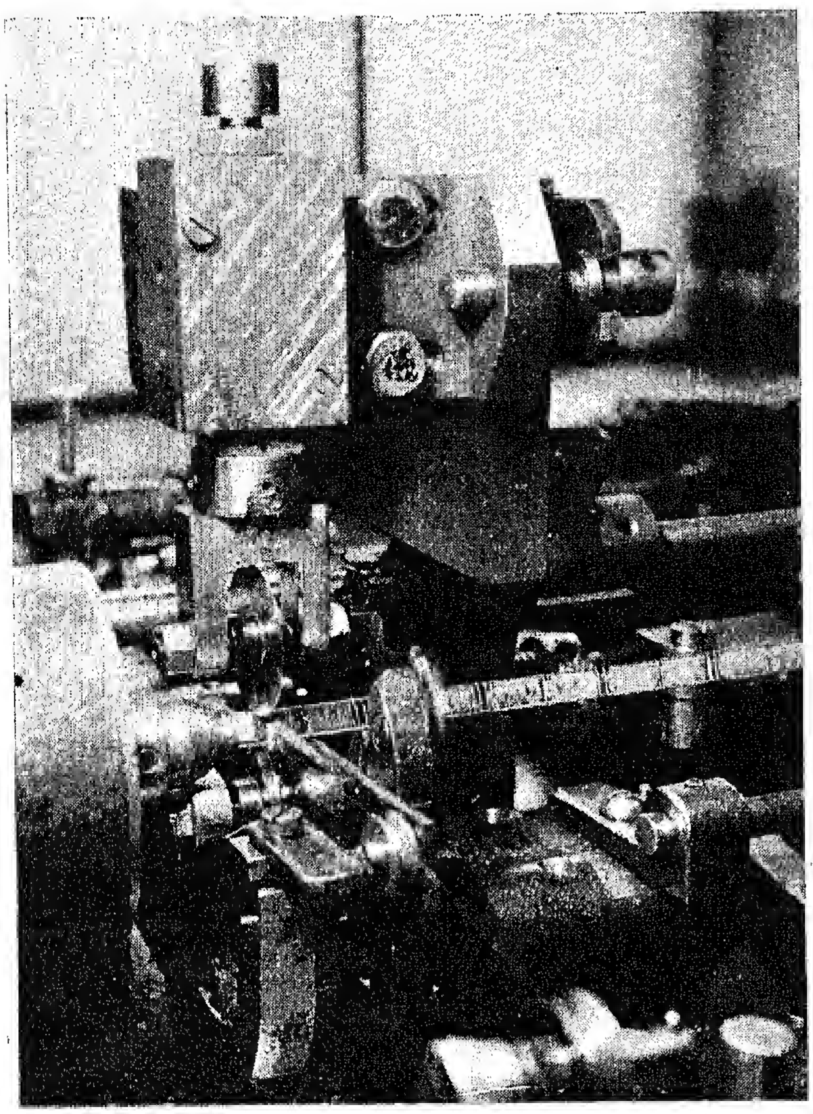


Fig. 27.—Grid-winding machine.

We have already indicated the degree of accuracy required in grid dimensions to ensure uniform characteristics. The importance of uniform mechanical properties of the wire used for winding grids, which are of course always slightly larger than the mandrels on which they are finally pressed or stretched, will be appreciated. The strain introduced during final shaping must be small, as otherwise distortion will occur on heating.

Equally important as the mechanical properties are the "gas properties" of the electrode materials. Here the term "gas properties" is intended to include not only the amount of gas which may be included in the metal (either "volume" or "surface" gas) but also the capacity of the metal to re-adsorb gas on its surface. This last factor is in some cases even more important than the first. An exhaustive study of the sources of gas in receiving valves has shown that the carbon dioxide adsorbed by the electrodes during decomposition of the barium-strontium carbonates on the cathode is far more difficult to remove than the residual gas existing in the metal, and that the nature of the surface of the electrodes has an enormous effect on this adsorption. Table 3 gives the relative adsorption of CO_2 on different surfaces during the decomposition of the cathode carbonates.

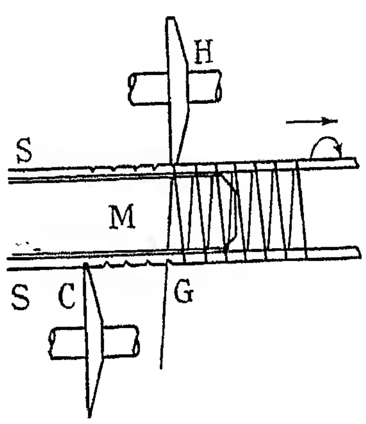


Fig. 28.—Grid-winding machine.

The "volume gas" in a metal may be permanently removed by heat treatment *in vacuo* or in hydrogen,* and Fig. 29 shows the effect on the "volume" gas in nickel of heat treatment at 1 000° C. The degree to which "volume" gas is removed in practice depends on the purpose for which the metal is being used. In support wires of grids, where the ratio of volume to surface is relatively large, it is important to reduce the volume-gas content to a low level, and a long degassing treatment of the wire, either during manufacture or subsequently, is necessary. On the other hand, in the case of sheet metal used for anodes and screens, where the ratio of surface to volume of metal is large, the volume gas is relatively unimportant, but the surface of the metal should be as smooth and bright as possible. From this point of view it is unfortunate that the valve manufacturer is compelled, for reasons stated elsewhere in this paper, to use anodes with carbonized surfaces (see Table 3).

* See Reference (20).

For insulating and spacing the electrodes from one another, mica is generally employed. It has distinct advantages over other possible materials in that it is mechanically strong even in thin sheets (approximately 0·3 mm. thick), it can be stamped too into flat plates of any desired shape with great accuracy, and it has just sufficient flexibility to allow the electrode support wires to slide easily through holes without becoming jammed.

Table 3

Surface	Relative adsorption
Nickel, degassed in vacuum, 15 minutes ..	1
Nickel, degassed in vacuum, 8 hours ..	2
Nickel, degassed in wet hydrogen, 15 minutes	20
Nickel, degassed in dry hydrogen, 8 hours..	8
Nickel, degassed in wet hydrogen, 8 hours..	400
Nickel, roughened surface	4 000
Nickel, roughened surface, exposed for 1 week	40 000
Nickel, carbonized surface	450

For temperatures up to 500° C., the insulating properties of best-quality muscovite (ruby clear mica) are exceedingly good; it is chemically stable and evolves little gas. Above this temperature, however, the mica rapidly decomposes with the liberation of water vapour, one of the most harmful gases in a valve, and electrolyses. In valves in which the insulators reach higher temperatures alumina, magnesia, or steatite, pressed from powdered material to the required shape, and sintered at 1 500°–1 800° C., are employed. Good-quality phlogopite mica, which is stable up to 700°–800° C., can also be used.

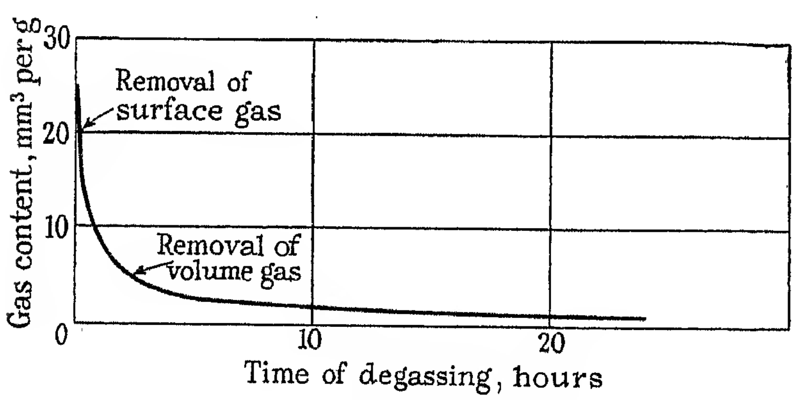


Fig. 29.—Effect of heating nickel at 1 000° C. in hydrogen.

For small receiving valves, the manufacture of ceramic insulators to a high degree of accuracy presents difficulties. Not only is the accuracy of the dimensions of the die used for pressing the powder important, but the shrinkage of the insulator during sintering, which varies considerably with the sintering temperature, must be closely controlled. One of the main objections to these insulators, and in fact the reason why they are not more generally employed, is the difficulty of locating the electrode supports in the holes. If the electrodes are a loose fit, the valve will be microphonic, while, on the other hand, a tight fit will prevent free expansion of the electrodes and distortion of the assembly will result. The difficulty can be overcome by special designs, but these involve considerable increase in cost, and are only employed where absolutely necessary.

CATHODES

One of the chief features of the modern receiving valve is the highly efficient oxide-coated cathode employed. It is proposed to discuss this type of cathode fully, but, before doing so, it is informative to review the various types of emitters that have, at various times, been used. In this way some of the difficulties of manufacture can also be considered.

Thermionic emitters can be divided into three groups: (*a*) Clean-metal emitters; (*b*) contaminated-metal emitters; (*c*) oxide emitters. The commercial development of each class of emitter followed the order given.

(a) Clean-Metal Emitters: Tungsten

The phenomenon of electron emission was first discovered in an electric lamp, and the thermionic valve was developed originally as an offshoot of the lamp. The desirable features in an emitter then, as now, were that it should possess reproducible thermionic characteristics, mechanical strength, and long life. Emission efficiency was not a very serious problem, since heating watts were not important, and the valve characteristics could be satisfied by employing multiple cathode systems. All the first valves were of the directly heated filament type, so that the cathodes consisted of a wire or series of wires. Tungsten, which was being used as a lamp filament, suited the requirements of the early valves very well. In order to obtain reproducible thermionic characteristics, it was essential that the metal surface should be free from gas and other impurities. Tungsten, because of its high melting-point (3 370° C.), could be raised to high temperatures on the pump, and its surface could thus be thoroughly cleaned. It could be operated at a temperature sufficiently high to ensure freedom from contamination by gas. The operating temperature was such that, although the filament had ample emission, it had a sufficiently low rate of evaporation to give a long life. The vacuum treatment was simple. The valve was baked and the filament was then flashed close to the melting point of the metal. The electrodes were bombarded in order to outgas them, and the valve was sealed off.

(b) Contaminated-Metal Emitters

(i) Thorium-on-tungsten.

In order to improve the mechanical properties of the tungsten used for lamp filaments, thorium oxide was added to the tungsten oxide during the manufacture of the tungsten, about 0·7 per cent thoria being obtained in the final wire. Langmuir* showed that thoriated tungsten had a considerably higher thermionic emission than tungsten at the same temperature. Thorium, obtained by reduction of the thorium oxide, diffuses to the surface of the tungsten, and at temperatures where bulk thorium could not exist a monatomic layer adheres to the tungsten surface, with the result that its work function is reduced.†

* See Reference (21).

† *Ibid.*, (22), (23).

The treatment of the thoriated tungsten filament was generally as follows:—

The electrode system was outgassed on the pump by high-frequency treatment, and by bombardment from the filament run under ordinary tungsten conditions. The valve was then sealed off, and the filament flashed near the melting point for a minute or so. This treatment cleaned the wire surface, and at the same time reduced some of the thorium oxide to thorium. The filament was then run at 2 200° K. At this temperature thorium diffused to the surface, and there formed the active layer. The operating temperature for these filaments was 1 900° K.

The thorium layer on the surface, being chemically very active, was easily "poisoned" by the presence of oxygen or water vapour. This danger could be avoided if the pumping time were prolonged. An alternative solution was to carbonize the filament. A small amount of a hydrocarbon vapour was admitted to the hot filament, and the hydrocarbon combined with the tungsten to form tungsten carbide. The usual method was to burn the filament in the vapour until its resistance had increased by 7 per cent. The thorium was produced by running the filament off the pump at 2 400° K. for several minutes. The carbide produced thorium by its reducing action on the thoria. The filament was then run at 2 200° K. in order to stabilize the emission. Furthermore, the filament was protected against "poisoning" by the presence of the carbide, which was preferentially attacked by gas and water vapour. The gaseous products of the attack were adsorbed on the walls of the glass bulb.

The main objection to the carbonizing process was the fact that the filament was rendered very brittle by the carbide, and valve losses in transport were very heavy. The solution to this trouble was the stranded filament. It was made very much as a 7-strand cable is made, i.e. six wires were twisted round a central wire of similar diameter. During carbonizing, only the exposed surfaces of each wire were carbonized, and the central wire remained unaffected. This filament was therefore much more robust.

The operating temperature for maximum efficiency is determined by the temperature necessary to maintain the optimum covering of thorium atoms, and this is too low to stop the cathode cleaning-up evolved gas. To counter this defect, a "getter," i.e. a layer of some substance that will adsorb gas, is deposited on the inside of the glass envelope. The early getter was phosphorus, which was originally used in lamps for removal of water vapour. Later getters were alkali or alkaline-earth metals. The action of getters is discussed more fully later in the paper.

(ii) Caesium-on-oxygen-on-tungsten (W-O-Cs).

The discovery that the work function of a metal was reduced when a layer of atoms of another electropositive metal was present on its surface led to much work on this form of emitter.* Generally, the more electropositive the contaminating metal is, the more the work function is reduced. A still greater reduction in work function is obtained when the contaminating film consists first of a layer of electronegative atoms such as oxygen, and then the layer of electropositive atoms. The most efficient form of this sandwich type of surface yet developed is caesium-on-oxygen-on-tungsten. The tungsten surface is prepared as follows: The tungsten is first oxidized. It is next heated in vacuum until only a monatomic film of oxygen remains, and caesium is then evaporated on to the surface from a suitable source. The final cathode is again heated in vacuum at a suitable temperature in order to obtain the maximum activity.

Despite the high emission efficiency of this type of emitter, it has never been successfully developed commercially. The properties of caesium valves have been extensively studied in the G.E.C. Laboratories, and the following facts have been established. The emission varies with temperature as shown in Fig. 30, and the operating temperature for maximum life is about 810° K. This low temperature is necessary because the degree of covering of the tungsten surface is a function of the vapour pressure of the caesium, and of the temperature of the cathode. The vapour pressure in turn is affected by the bulb temperature. The emission density is very low, so that an extremely large cathode area is necessary and microphonic problems in filamentary types become in consequence much more serious. The cathode can only be operated with very low anode voltage ($\ngtr$ 120 volts), because positive ions will readily remove the caesium atoms by a bombardment process. Judged from a manufacturing standpoint, a very high degree of skill is required to make this form of cathode, and it has so far proved unsatisfactory for commercial development.

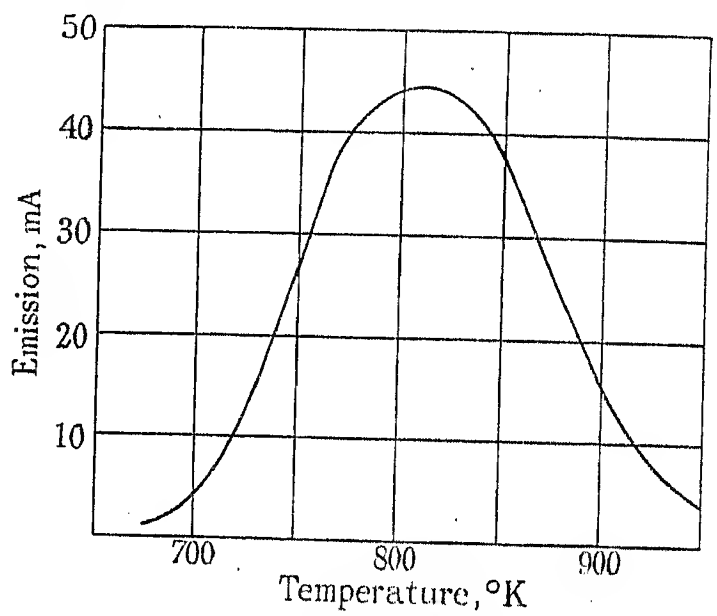


Fig. 30.—Emission from W-O-Cs.

* See References (24), (25), (26), (27).

(c) Oxide Emitters

(i) The alkaline-earth oxides.

As early as 1904, Wehnelt* showed that the emission from a metal wire coated with calcium oxide was very high when compared with the emission from the metal itself. It was not until 1920, however, that this form of emitting cathode was used commercially by the Western Electric Co.†

The demand for highly efficient cathodes which were

* See Reference (28).

† See discussion.

Plate 1

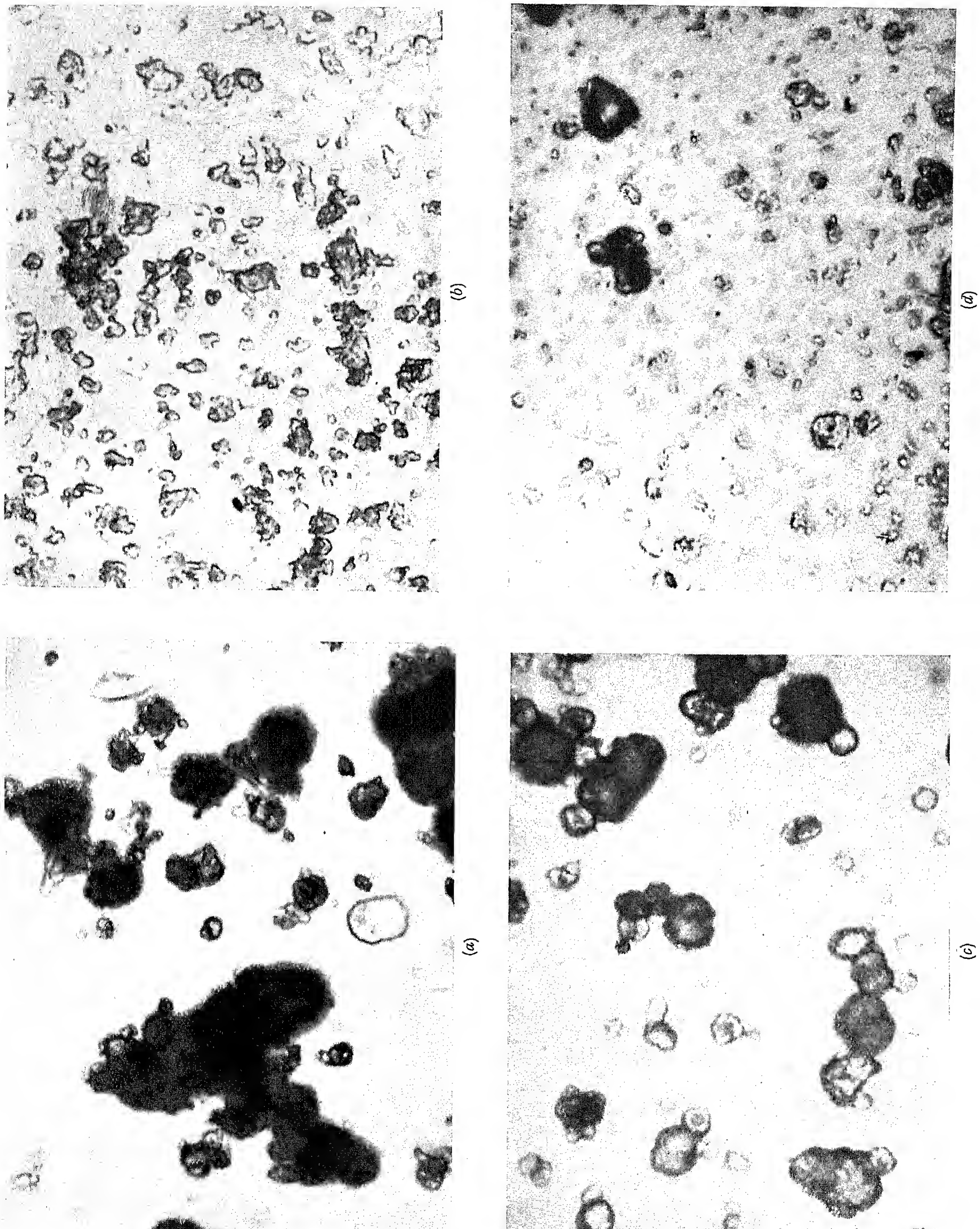
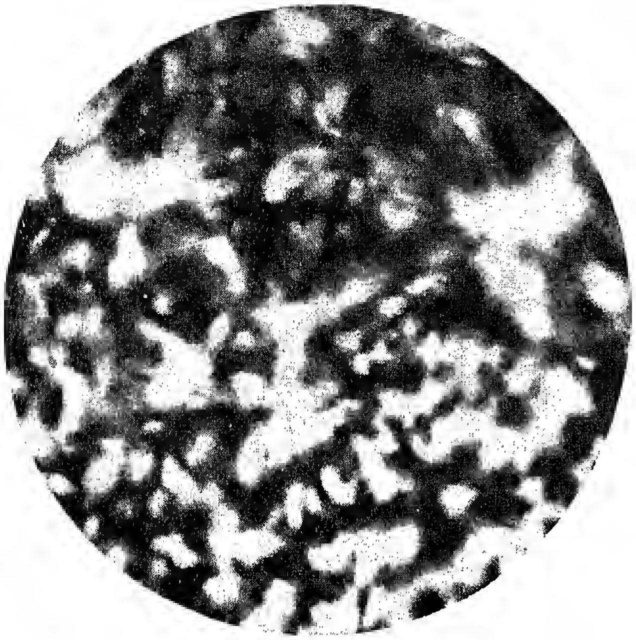


Fig. 32.—Effect of method of precipitation on particle size of double carbonate. (Magnification 1 000.)

(a) Precipitation using $NH_4OH + (NH_4)_2CO_3$.
(c) Precipitation using $CO_2 + NH_4OH$.
(b) Precipitation using Na_2CO_3.
(d) Precipitation using $CO_2 + NaOH$.

Plate 2



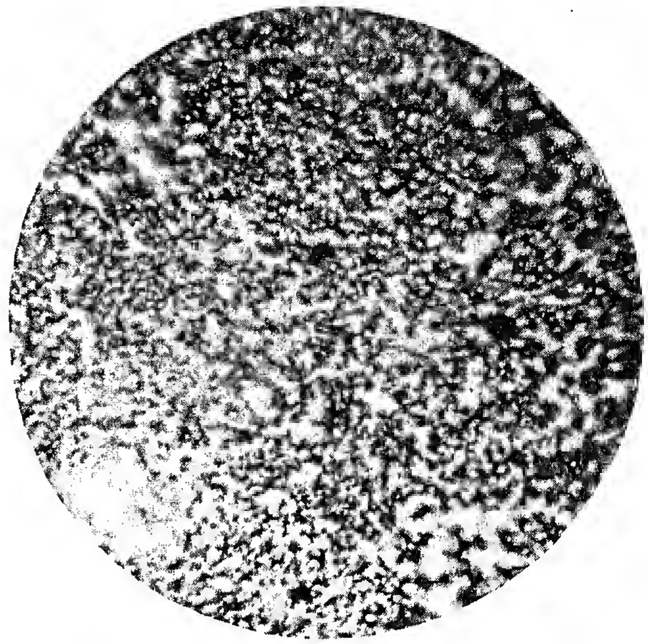


Fig. 33.—Electron-microscope photographs. (Magnification 200.)

(*a*) Carbonate coating shown in Fig. 32(*a*).

(*b*) Carbonate coating shown in Fig. 32(*b*).

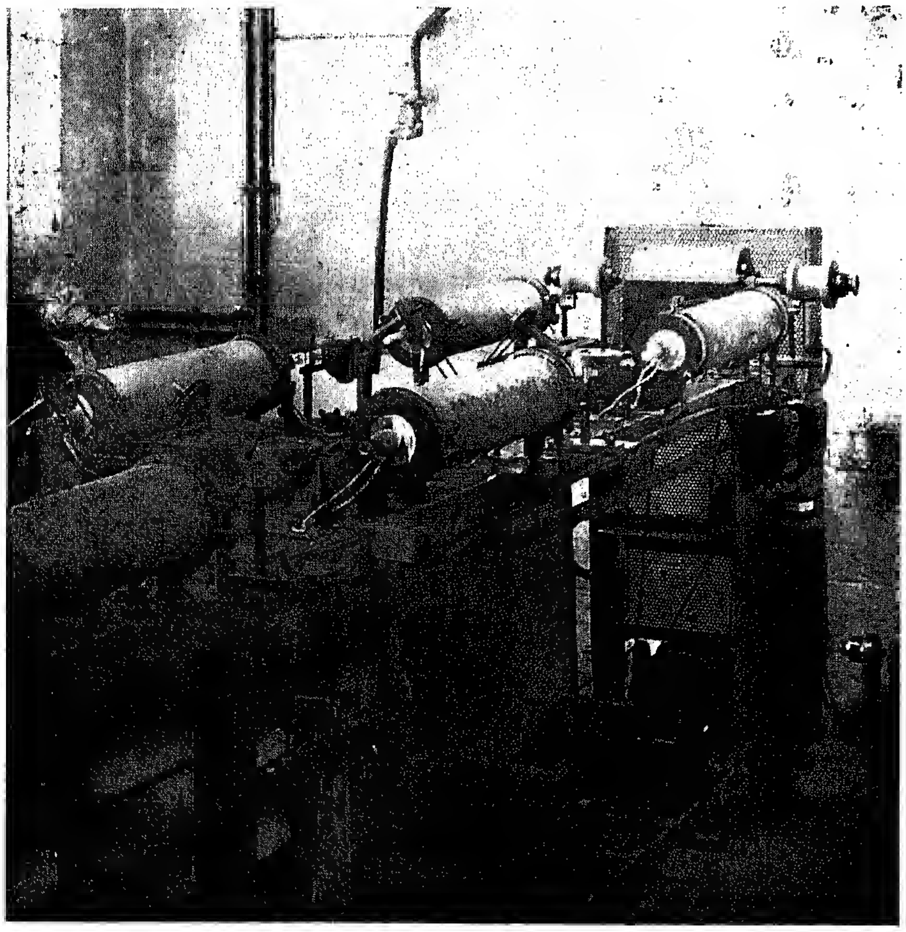


Fig. 35.—Filament-coating plant.

Fig. 43.—Screened output pentode.

inexpensive to operate, focused commercial attention on the oxide emitters. A considerable improvement in the standard of high-vacuum technique had to be achieved, however, before general commercial manufacture could be contemplated. We have seen that, as the emitter becomes more efficient, the degree of vacuum becomes increasingly important, because of the "poisoning" effect of gas on the emitter. The oxide cathodes are generally produced in the evacuated bulb, and a large quantity of gas has to be removed from the valve before any activation of the cathodes can be attempted. Two processes have been in general use. In Europe, the process was to plate a tungsten wire with a thin film of copper. The copper was oxidized, and the alkaline earth, usually barium, was obtained by decomposition of the alkaline-earth azide. The barium metal combined with the copper oxide to form barium oxide.

This process, the vapour process, was introduced by the Philips Lamp Co., of Holland. The process had one distinct advantage: the large quantities of barium liberated during the distillation acted as a very efficient getter, both on the pump and during life.

In America, the oxide was formed by coating a wire with a paste of the carbonate or hydroxide. This paste, when raised to a suitable temperature in a vacuum,

Table 4

Emitter	Efficiency	Emission density	Operating tempera-ture	Work function
	mA per watt	mA per cm.^{2}	°K.	volts
W ..	1 to 5	274	2 500	4·52
W-Th ..	20 to 25	3 000	1 900	2·77
W-O-Cs ..	700	126	810	0·7
BaO, SrO, CaO	150 to 250	250	1 040 to 1 100	0·95

decomposed to form the oxide. The gas evolved had to be pumped away, and getters were employed during pumping in order to maintain a high vacuum.

The vapour process lost favour when the necessity for indirectly-heated cathode valves arose. The distillation of barium introduced leakage between electrodes, and this leakage resulted in very noisy valves. To-day practically all makers of receiving valves employ the paste oxide type of cathode.

Table 4 summarizes the properties of types of emitters mentioned, and gives the results obtained over a number of years in the organization with which the authors are associated.

(ii) Mechanism of the emission.

The theory generally accepted* is that the alkaline-earth oxide coating behaves as an electronic semi-conductor. It conducts because of the presence of the right kind of impurity atoms, in this case barium atoms. The barium atoms are produced from the oxide, and it is these barium atoms which supply the conducting electrons. These electrons are finally emitted into vacuum because of the presence of a monatomic film of barium on the surface of the oxide. If certain assumptions are made, it can be shown that the Richardson equation

$$I = A\theta^2 e^{-(\phi-\mu)/k\theta} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

holds for these oxides. μ, the inner potential, is given by

$$\mu = \tfrac{1}{2}(W_1 + W_2) + k\theta \log \frac{\alpha N_0^{\frac{1}{2}}}{(\beta\theta)^{\frac{3}{4}}} \quad . \quad . \quad . \quad (9)$$

where W_1 and W_2 are energy levels in the oxide, α and β are constants, and N_0 is the number of barium atoms per cm.^{3}; so that the work function depends on the concentration of barium atoms.

(iii) Chemical composition and physical state of practical oxide coatings.

The usual oxide coating consists of barium and strontium oxides present in equimolecular proportions or equal parts by weight. The oxides are usually obtained by decomposition of the carbonates in vacuum. It has been established that under ideal vacuum conditions, a mixture of the two oxides has a

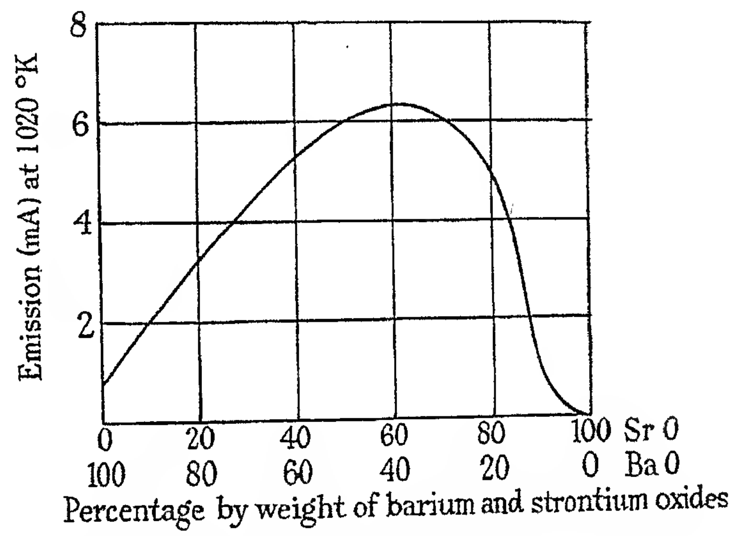


Fig. 31.—Emission from solid solution of barium and strontium oxides.

higher emission than either of the single oxides. The maximum emission is obtained when, for a given chemical composition, the oxides are present as a homogeneous solid solution. In Fig. 31 the relation between emission and chemical composition of the double oxide is shown. The theoretical reasons for the necessity for the double oxide are discussed elsewhere.* The emission also appears to be a function of the particle size of the double oxide. Thus, the three main features of the cathode coating are: (1) it should be a homogeneous solid solution of barium and strontium oxides. (2) It should have the correct oxide composition after final treatment in the valve. (3) The mixed oxide particles should be as small as possible.

Condition (1) is achieved by correct preparation of the original carbonates. If the carbonates are in solid solution, then they invariably give a double oxide when decomposed in a vacuum. The double carbonate is obtained by simultaneous precipitation from a hot alkaline solution of the nitrates.

Condition (2) is achieved by using the correct amount of each nitrate, and by ensuring that the nitrates solution is alkaline. Otherwise preferential precipi-

* See Reference (22).

* See References (29), (30).

tation of the strontium carbonate occurs, and the resulting carbonate may have two or more phases of varying chemical composition. On heating the double carbonates in vacuum, the temperature must be controlled, or else a change in chemical composition of the resulting oxide may occur. This point will be amplified under the heading " Pumping Technique."

Condition (3) depends on the way in which the precipitation from the nitrates solution is carried out. The exact nature of the precipitating agent, the alkaline agent used, temperature, speed of precipitation, and the solution strengths employed, are all important factors. Although there is not space to describe the various methods, the photomicrographs in Fig. 32 (Plate 1, facing page 416) illustrate the range of particle sizes that can be obtained. Recently, E. Patai and Z. Tomaschek* have described a method for obtaining carbonate particles of colloidal dimensions.

The authors are now studying the effects of the carbonate particle size by means of the electron microscope. Although the results obtained are not yet conclusive, it may be of interest to show just how two

nickel; its thermal emissivity is much lower, and since, in practice, the temperature of the coated cathode is dependent on the thermal emissivity of the core and the thickness of coating, a coated copper cathode will require less power to maintain it at a given temperature than a similarly coated nickel cathode.

Curves showing the temperatures of coated copper and coated nickel at the same watts input per cm² are given in Fig. 34. It will be seen that the temperature of the coated cathode depends on the coating thickness, and that at a given temperature a copper cathode requires about 25 per cent less power than a nickel cathode.

The chief disadvantages of copper are: (1) Its lower melting-point (1 080° C., as against 1 450° C. for nickel). (2) Its greater volatility (evaporation takes place at temperatures as low as 730° C.). It is therefore necessary to activate a copper cathode at a lower temperature than that employed for nickel (1 100° C.), and to operate the cathode at a maximum temperature of 730° C. At higher temperatures, any evaporation which takes place will give rise to electrical leaks and noisy valves. For these reasons, nickel is to be preferred as a core material,

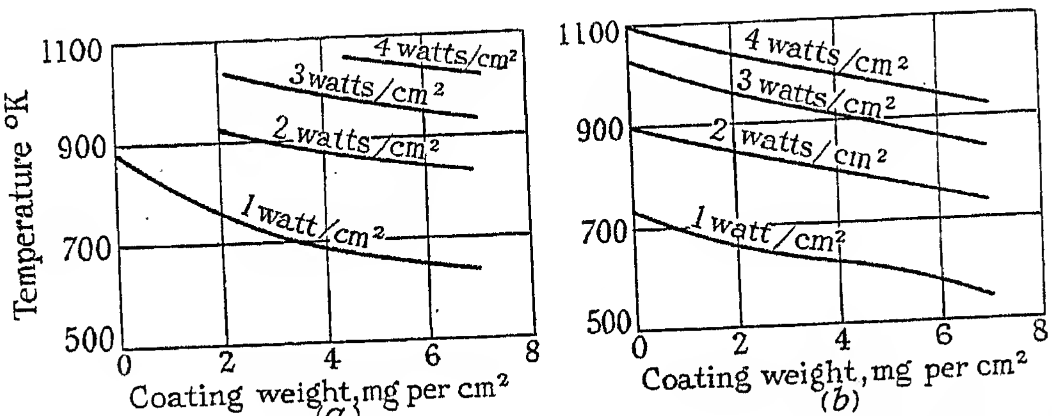


Fig. 34.—Effect of coating weight on temperature of coated copper and nickel cathodes.
(a) Copper cathode.
(b) Nickel cathode.

coated surfaces which differ only in the particle sizes of the original carbonates exhibit very different emission characteristics. In Fig. 33 (Plate 2) are shown the electron photomicrographs of two cathodes, one coated with the coarse-particle double carbonate and the other with the fine-particle double carbonate shown in Fig. 32. It will be seen that while the emission density is very much the same for both, the total emitting area is very much greater in the case of the fine-particle carbonate. The photographs are reproduced here so that the importance of particle size can be visually appreciated.

(iv) The core material.

The essential features of the core material are that it shall be mechanically strong, easily worked, have a high melting-point and low thermal emissivity, and be inexpensive.

Nickel, copper, silver, gold, platinum, and various alloys of these metals are all possible core materials. Tungsten cannot be used, because shaped indirectly-heated cathodes are extremely difficult to make. Platinum and gold are too expensive, and silver is too volatile. Therefore, nickel or copper, both of which are cheap, might be used. Copper has one advantage over

* See Reference (31).

and it is the core metal normally used by all valve makers.

It has been shown* that, in order to obtain the best thermionic results, certain metallic impurities, which will act as reducing agents to the oxide coating, are desirable in the nickel. These impurities increase the barium concentration by their reducing action, and so assist in improving the thermionic emission. Suitable metals are aluminium, magnesium, titanium, the rare-earth metals, and silicon. The actual amount and nature of impurity added is governed by the ease of manufacture of the nickel alloy, and by the following considerations: (1) Effect on thermal emissivity of the nickel (generally increased). (2) Effect on electrical resistance of the nickel (generally increased). (3) Effect on mechanical strength of the nickel (generally increased).

In the case of indirectly-heated cathodes (1) is the chief consideration. For directly-heated cathodes, some adjustment can be made to diameter and length which will offset the effects of (1) and (2). In practice, the authors have found that, for directly-heated filaments, a nickel + 2 per cent aluminium alloy is satisfactory. For indirectly-heated cathodes, the presence of up to 0·1 per cent of magnesium is best.

* See Reference (32).

Attempts have been made to introduce barium directly into the core. Alloys of nickel and barium which contain more than a trace of barium are extremely difficult to make, and nickel-barium alloy cathodes have not yet been used commercially.

(v) Coating processes.

For directly-heated cathodes, in the form of a wire or strip the cathodes are made by drawing the wire through a series of baths and ovens. The apparatus is illustrated in Fig. 35 (Plate 2). The baths contain a water suspension of the carbonates together with about 12 per cent of barium or strontium nitrate, which acts as a binder. After passing through a bath, the wire passes through the oven at 750° C. The atmosphere is generally one of CO_2 in order to avoid any decomposition of the carbonates, and the authors have found that oxidation of the core due to nitrate decomposition can be avoided by the use of suitable mixed gases. This is important, as core oxidation slows up the cathode activation. In the oven the coating is

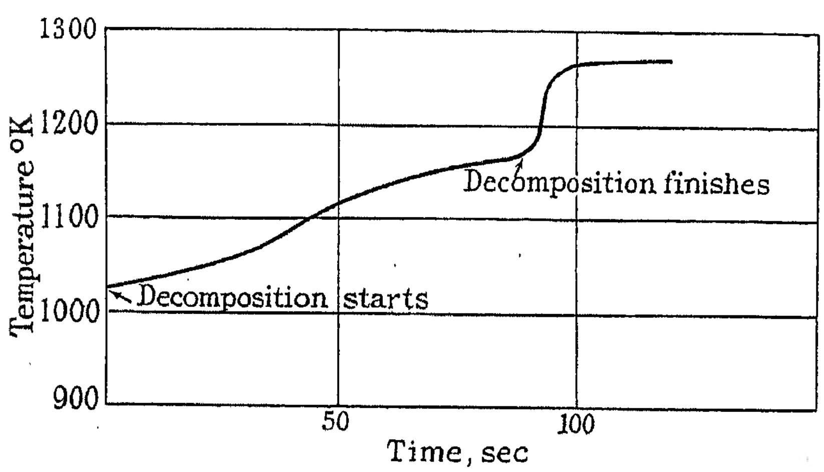


Fig. 36.—Cathode temperature-changes during degassing at 5·9 watts per cm.².

sintered on (the nitrates decompose to form carbonates) and the final coating consists of a homogeneous double carbonate. This coating and sintering process is repeated until the required weight of coating is obtained.

For indirectly-heated cathodes, a suspension of carbonates in an organic solvent is made and sprayed on to the nickel base. The degree of adhesion of the coating to the core metal is governed by the nature of the diluent used and by the actual spraying conditions. The following factors are also important—stable viscosity of the spraying suspension, temperature of spraying, fineness of the carbonate particles.

The carbonates are decomposed to oxides by heating them on the pump. The carbonates begin to decompose at 750° C. An important factor in manufacture is that the time of decomposition should be kept as short as possible. In order to avoid evaporation of the coating, however, the temperature of the coated cathode must never exceed 1 100° C.

An additional complication is that the thermal emissivity of the coating falls when it changes from carbonates to oxides, so that a rise in temperature occurs although the watts supplied remain the same. A curve showing temperature-changes and time of decomposition of the carbonate is given in Fig. 36.

HEATERS

(a) Core Material

In indirectly-heated types, the cathode is normally a hollow tube of circular, oval, or rectangular section, which is heated by means of a filament inside the cathode, but insulated from it. The core material is generally tungsten. Since the heater wire normally runs at a temperature several hundred degrees above that of the cathode surface, it is essential that the wire should have a high melting-point. One of the disadvantages of tungsten, however, is that it is prone to brittleness at high temperatures. The brittleness, caused by crystal growth, can be avoided if 0·02 per cent alumina is added to the tungsten. This prevents temperature recrystallization below 2 000° C.

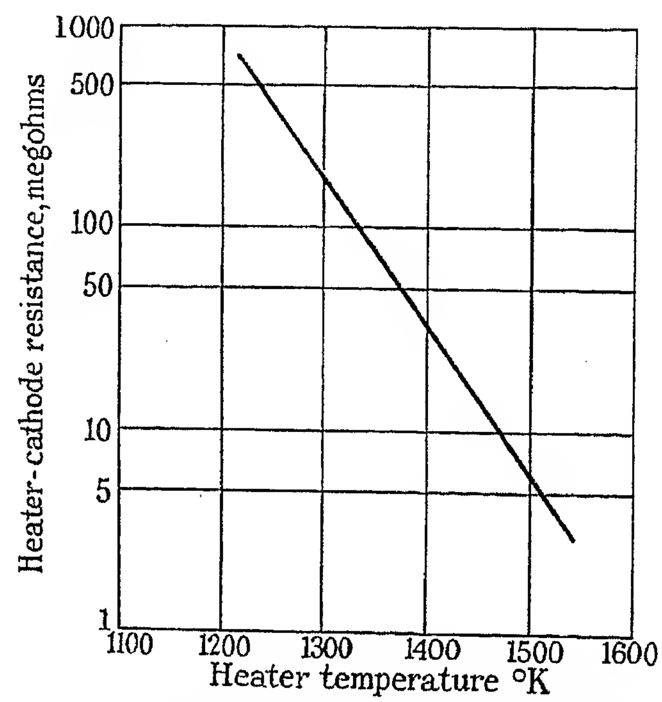


Fig. 37.—Electrical resistance of alumina coating.

Another form of core wire now being used consists of a molybdenum-tungsten alloy. This alloy was first introduced in America, and the advantages are that the alloy retains the ductility associated with the molybdenum, and yet has a melting-point well above that of molybdenum, and a vapour pressure which is negligible below 1 750° C.

(b) Insulating Material

The insulating material consists of a refractory such as alumina which is sprayed on to the heater. The heater-cathode insulation, which must be as high as possible for circuit reasons, depends on: (1) The temperature of the heater. (2) The nature of the insulator used.

(1) A curve, showing variation in the heater-cathode insulation with temperature, for alumina-coated tungsten, is shown in Fig. 37. It is essential to design the heater to run at as low a temperature as is possible.

(2) The current/voltage curve for a typical alumina coating is shown in Fig. 38. It will be seen that a higher current flows when the cathode is positive with respect to the heater, and that it saturates. There is reason to believe that the alumina behaves as an impurity semi-conductor, although it is difficult to

determine whether the leakage current is carried mainly electronically or electrolytically. There appears to be no doubt, however, that the purer the alumina the

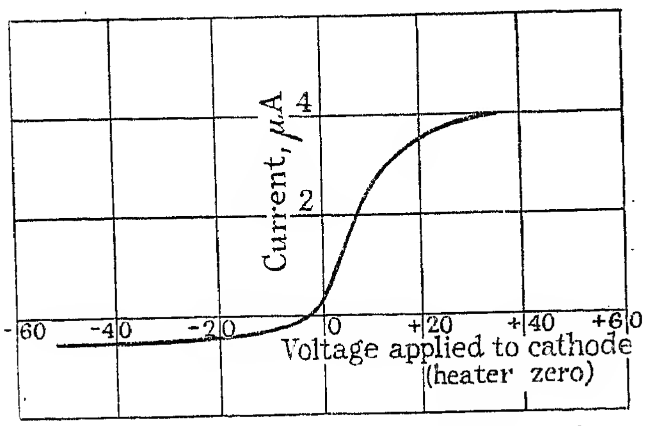


Fig. 38.—Current/voltage characteristics of alumina coating.

higher the insulation. The chief impurity in alumina is sodium, present as sodium aluminate, and this must be removed as far as possible by chemical means. The following treatments are usually given to the alumina:—

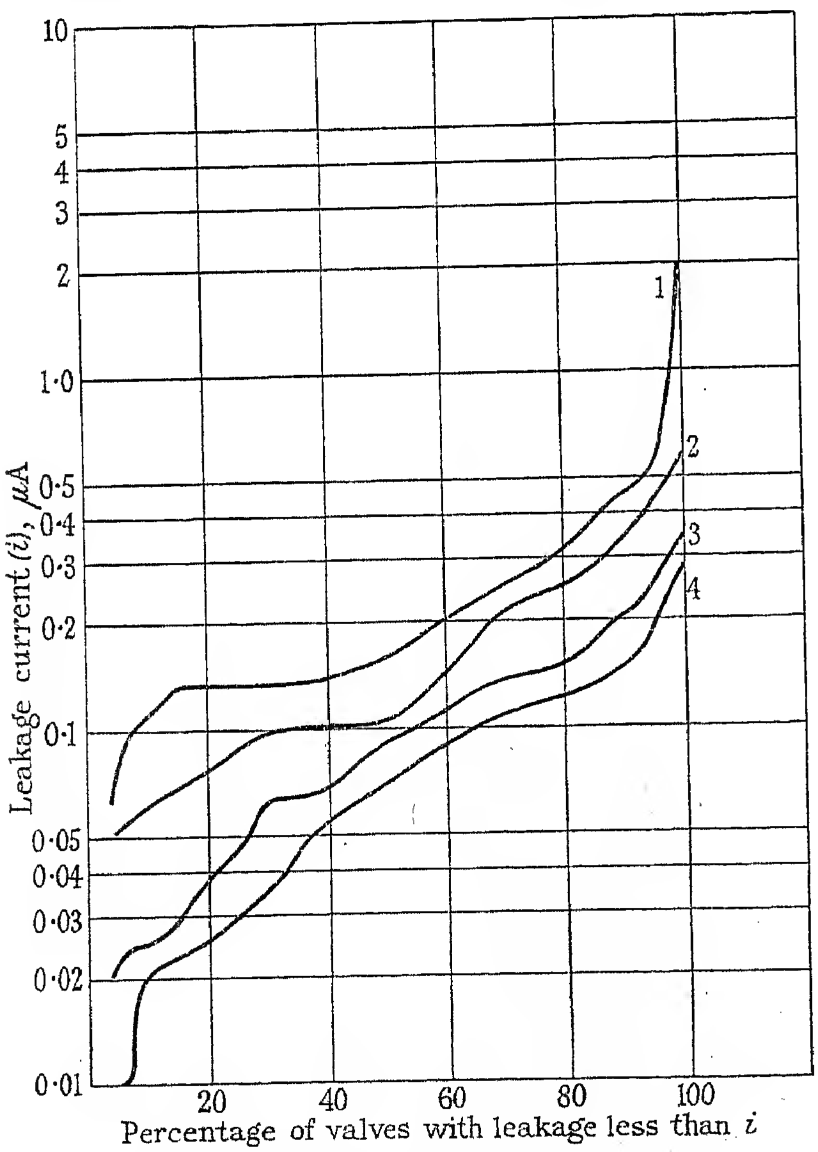


Fig. 39.—Insulation distribution curves.

Curve 1. Alumina.
Curve 2. Washed alumina.
Curve 3. Alumina presintered at 1 750° C.
Curve 4. Alumina + 1 per cent BeO.

(i) As much alkali as possible is removed by prolonged acid washing. Generally the alkali can be reduced to 0·02 per cent. It is essential to store the washed alumina so that atmospheric contamination is reduced to a minimum.

(ii) After spraying, the coated heater is heated in

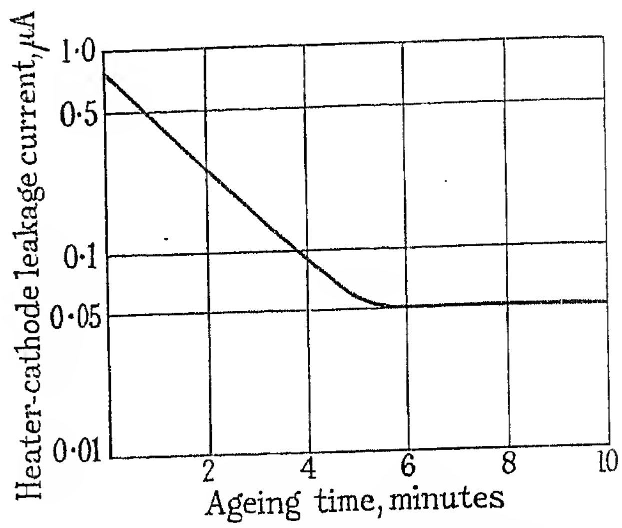


Fig. 40.—Effect of ageing with + 45 volts applied to cathode, for alumina coating.

hydrogen at a high temperature. This removes the binder, sinters the coating, and removes a certain amount of sodium and other impurities. Sometimes it is necessary to sinter the washed alumina in hydrogen at 1 600° C. before it is used for spraying purposes.

One other method of improving the insulation has been found to be effective. If a small amount (1–2 per cent) of beryllia is added to the alumina, the insulation is improved to a level reached by taking the precautions described above. It appears that the beryllia combines with the alumina to form a compound of the type $(BeO)_y(Al_2O_3)_x$. Its exact formula has not been established, but it is not the ordinary beryllium aluminate. It may be that in this compound the different crystals produced may have different energy levels, which result in the altered conductivity.

The effect of these treatments on the insulation is shown in Fig. 39. It is a remarkable fact that at the operating temperature of the heater (1 400° K.), heater-cathode resistances of 80 megohms or more can be obtained.

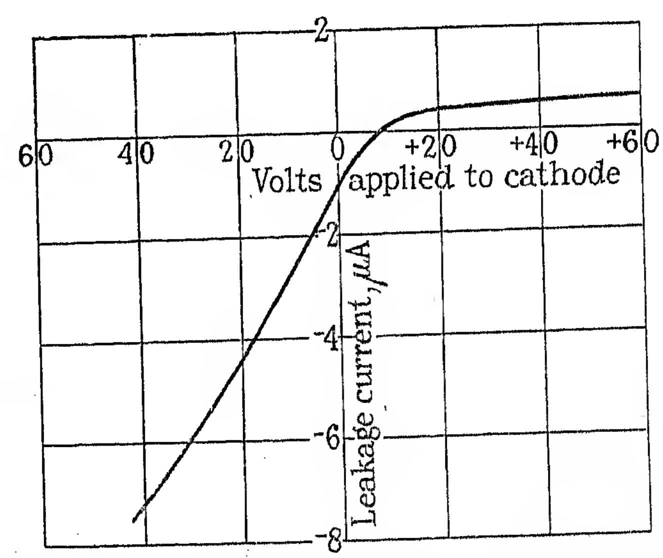


Fig. 41.—Current/voltage characteristic of magnesia coating.

One other feature leading to poor insulation is contamination by handling during assembly. It is not always possible to avoid this, and the remedy is to apply

a potential between heater and cathode during ageing. A "poisoning" of the conductivity occurs, and the insulation improves. The improvement is permanent, but the reason is not clear. The effect is shown in Fig. 40.

Magnesia has been used as an insulating coating, but the authors have found it to be unsatisfactory. It can be readily obtained pure, but it cannot be sintered in the presence of tungsten without some combination occurring. Further, at 1 700° C. magnesia has an appreciable vapour pressure, so that coating may be lost during sintering, and during pumping. In the valve, the heater lighting treatment results in further reaction between the magnesia and the tungsten core, and a compound of the tungstate class is formed. The electrical characteristics of a magnesia-coated tungsten wire are extremely interesting, and are shown in Fig. 41. It will be observed that initially the greater current

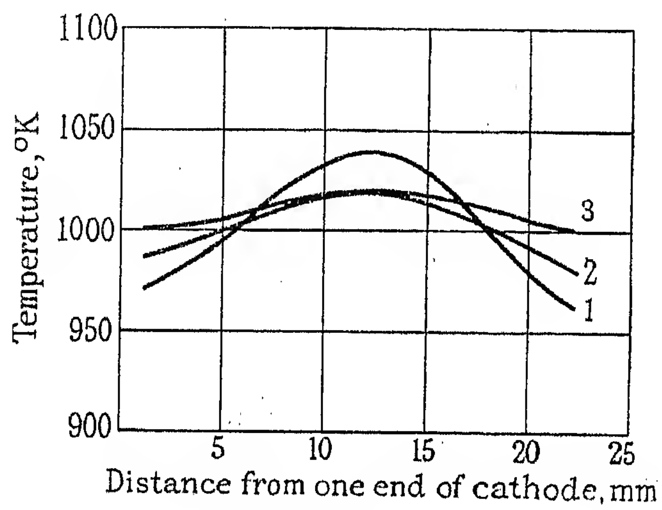


Fig. 42

Curve 1. Single hairpin heater.
Curve 2. Reverse helix heater.
Curve 3. Single coil heater with centre return lead.

flows when the cathode is negative with respect to the heater, but prolonged running with the voltage applied so that the cathode is positive (the normal condition) results in electrolysis of the coating, and tungsten is deposited on the coating surface adjacent to the cathode. A short-circuit results, and the heater fails. The objections to magnesia coatings apply to magnesia tubes, which have been used by valve makers to sleeve tungsten heaters.

(c) Heater-Cathode Design

In indirectly-heated valves the design of the combined heater-cathode system is important, judged from the standpoint of emission efficiency. For a cathode of a given area, dissipating a given number of watts, it is desirable that the energy should be distributed as evenly as possible over the cathode surface. With the ordinary hairpin type of filament, the temperature-difference between the end and centre of the cathode may be as high as 80 deg. C. This can be brought down as low as 5–10 deg. C. by suitable heater design.

The operating temperature of the heater is decided largely by the disposition of the heater in the cathode, for the latter is heated mainly by radiation (any conduction can only take place at a number of points or live contacts). It follows, therefore, that the lowest temperature of a heater which is dissipating a given number of watts, will be obtained when the radiating area of the heater is the greatest. Thus the most efficient heater would be a close-fitting cylinder. The nearest approach to this is a single helix wound with turns as close together as is possible.

In Fig. 42 are some interesting curves for temperature distribution along the cathode, when various shapes of heaters are used. It must be borne in mind that heater design is influenced by such factors as magnetic-hum effects and coating problems, so that it may not always be possible to use the lowest-temperature heater. One other disadvantage of low-temperature heaters is their greater heating-up time due to their larger thermal capacities and smaller differences between their cold and hot resistances. In Table 5, characteristics of a cathode with three different heaters are given.

"GETTERS"

A getter is used for maintaining the vacuum in a valve after it has been sealed off. The alkaline earths, the alkali metals, and magnesium, are common getters;

Table 5

Heater	Heating-up time of cathode	Temp.-diff. between centre and ends of cathode	Operating temperature of heater
	sec.	°C.	°K.
Hairpin	11·2	80	1 460
Double helix ..	15·0	40	1 400
Single helix ..	17·9	10	1 360

and the getters mostly used to-day are an alloy of barium and magnesium, and barium. The alkaline-earth oxides, singly or mixed, are also good getters.

(a) Method of Use

(i) Metal getters.

If the metal is relatively stable in air, it is welded to a metal disc and dispersed by high-frequency heating of the disc. If the metal of which the getter is composed is an unstable one such as barium, it is packed inside a closed container before welding. The high vapour pressure generated on heating is sufficient to burst open the closed ends of the container, and the metal is dispersed. In order to avoid any deposits forming over the electrode bonding system and so causing electrical leaks, the getter dispersal is usually directed towards the bulb wall by a suitable design of container.

(ii) Non-metallic getters.

Where very high inter-electrode insulations are required, as in certain special types, the non-dispersed form of alkaline-earth oxide getter is used. This is usually sprayed on to a metal disc in the form of cathode coating, and decomposed by high-frequency heating to the oxides. The oxides, when cold, act as getters. Although the authors believe this to be the first time that the oxides have been used in this way, for many years some valve manufactures applied a paint of alkaline-earth carbonates to the pinch.

It will be appreciated that since the emitting cathode itself is a mixture of alkaline-earth oxides, it too, in the active state, will adsorb gas, and this point must be carefully watched when valves are being made.

(b) Mechanism of Clean-Up

The gettering action of dispersed metals is twofold.* During dispersal a clean-up occurs, referred to as "volume gettering." Then when the gas comes into contact with the dispersed getter deposit a second gettering action occurs, known as "contact gettering." The gas is taken up either because it is adsorbed into the metal, or because it combines chemically with the metal. The actual nature of the clean-up depends on the type of getter, the nature of the gas, and the conditions prevailing at the time. For example, magnesium will adsorb hydrogen in contact with it, and this can be liberated again by heating the magnesium deposit. It will not adsorb CO_2, except under discharge conditions. Sodium will not getter hydrogen except under discharge conditions, and then it chemically combines with it to form the hydride. Barium will adsorb all the permanent gases, and it forms chemical compounds with oxygen and hydrogen. Hence barium is the most desirable getter, because of its affinity for most gases, and because the chemical nature of the clean-up means that the gas will be held even when the getter surface is hot.

The alkaline-earth oxide getters clean up by an adsorption process and are most efficient when dealing with CO_2. The gas is easily liberated on warming or by electron bombardment.

(c) Precautions in Use

Since getters may liberate adsorbed gas when warm, they should be deposited on the coolest part of the system. Direct electron bombardment may also liberate gas, and care should be taken to put the deposit in such a position that it is unlikely to acquire a positive potential. If possible, the getter deposit should be at cathode potential. In any case, since the metal disc always contains some getter residue, it is desirable to connect it to the cathode.

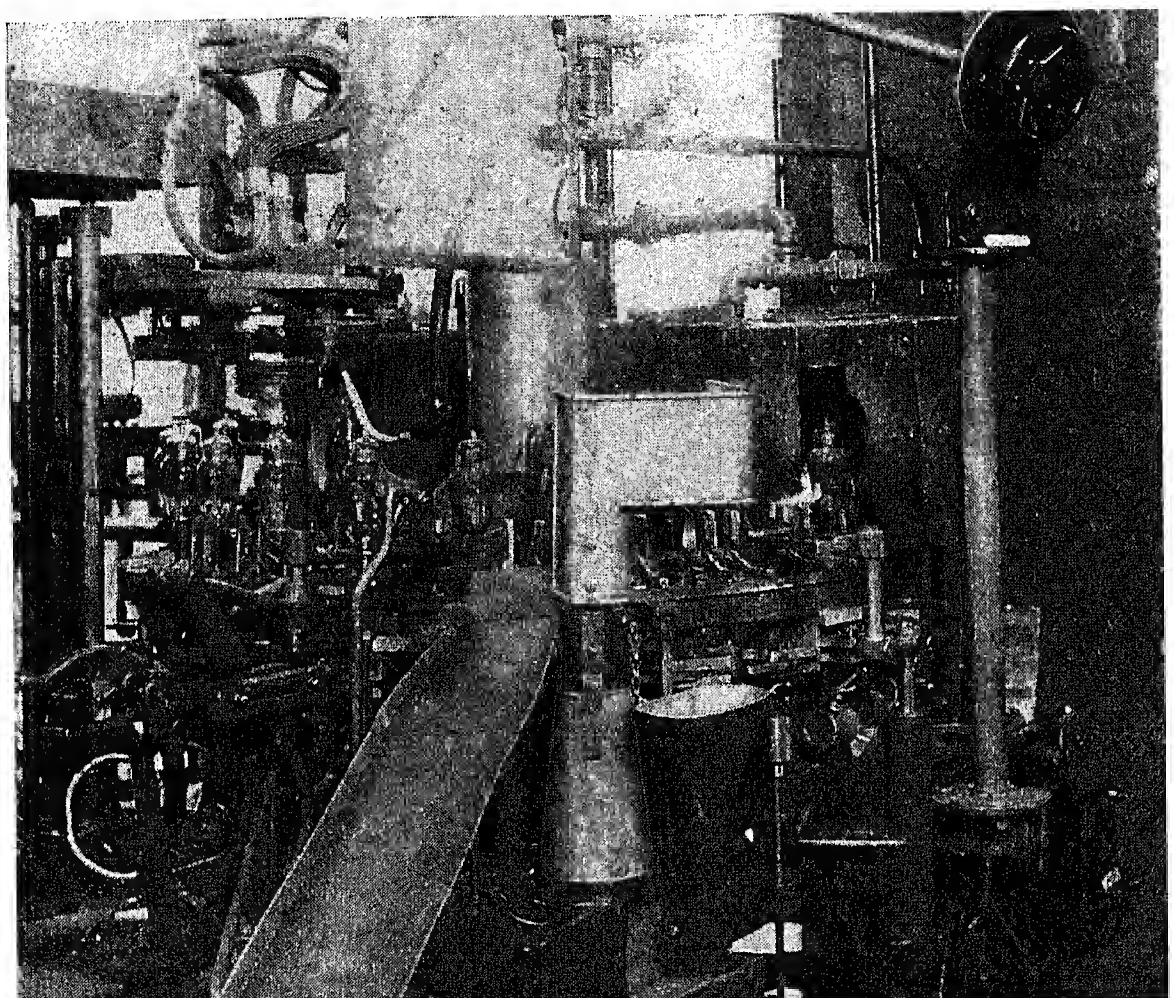


Fig. 44A.—Pumping unit.

PUMPING TECHNIQUE

The pumping of a modern receiving valve is designed to remove the greatest amount of gas in the shortest possible time. All the materials used are rendered as gasfree as possible before assembly (see section on "Properties of Materials"), and the completed valve is heated on the pump to remove any remaining gas. In Fig. 43 (Plate 2) a complete valve assembly of a power output (type N43) valve, including the heater, cathode, multiple electrode system, and getter, is shown. The pumping system used consists of a series of 2-stage machine pumps. Figs. 44A and 44B respectively show photographs of a pumping unit and a battery of pumps. The speed of pumping is given in Fig. 45.

The pumping procedure is as follows: (*a*) The system is baked at 450° C. in order to remove water vapour.

* See Reference (33).

(*b*) The electrode system is heated by high-frequency induction in order to remove adsorbed gas. (*c*) The cathode is heated in order to decompose the carbonates, the electrode system again being heated to prevent it picking up cathode gas. (*d*) The getter is dispersed, and the valve sealed off. The time taken to treat an individual valve varies according to type, but a speed of 400 valves an hour is an average figure when using a unit of the type shown.

The precautions to be observed are as follows: (i) The electrode system should be heated in such a manner as to ensure that excessive peaks of gas pressure are avoided. (ii) The cathode temperature should be maintained throughout the pumping process, since once the carbonates are decomposed the cathode is in an active state, and, as has already been pointed out, it will adsorb gas at low temperatures. (iii) The getter should be dispersed when the pressure is low, so that it is not employed in cleaning-up gas from the pump system. For this reason, the valve should be sealed off as soon as the pump has had time to remove any gas liberated by the gettering operation.

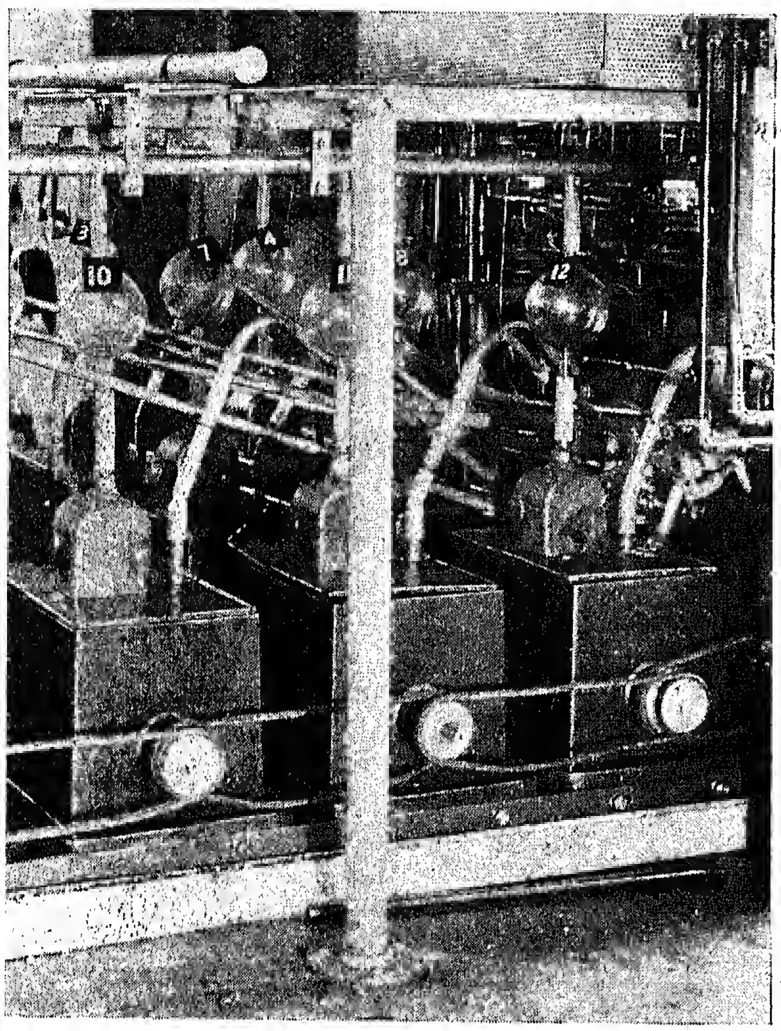


Fig. 44B.—Battery of pumps.

ACTIVATION PROCESS

The process of keeping the cathode hot after decomposition results in partial activation of the cathode. Activation is completed by drawing current from the cathode whilst it is run at a temperature of 900° C. The electrolytic process going on in the coating results in the formation of more barium, and the space current grows with time. Further, the voltage across the valve and the current flowing ionize any gas present, and enables the getter to clean it up. The time and nature of the activation depend on the specific type, but as a general rule the cathode is run at 850°–900° C. with all other electrodes strapped at a common positive potential, and a space current of 100 mA per cm.^{2} is drawn for 2–5 minutes. The valve is then run for 30 minutes under normal operating conditions, except that the cathode temperature is still maintained at 850°–900° C.

The initial bombardment period cleans the first grid surface, and any barium deposited from the cathode during the second period comes down on to a clean surface. This is important, particularly in high-μ types. The contact potential between grid and cathode determines the voltage at which grid current starts, and the activation schedule outlined above enables some measure of control to be exercised over the contact potential.

VALVE LIFE

(a) Emission Life

The life of the finished valve depends on the temperature of the cathode, and its resistance to poisoning by evolved gas.

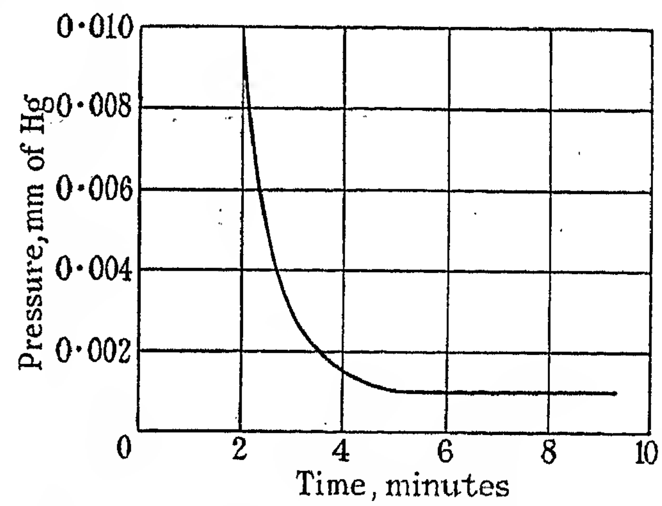


Fig. 45.—Pumping speed of a machine pump.

As is shown in Fig. 31, the emission from the solid solution of oxides is a function of the proportions of each oxide present. The oxides evaporate, and the barium oxide is considerably more volatile than the strontium oxide. Thus if the coating is run at such a temperature that appreciable volatilization of BaO occurs, the composition of the solid solution changes and the emission slowly falls. The rate of fall decreases with time, because the rate of evaporation of BaO decreases with increasing strontium content. The lowest possible temperature consistent with the emission demand will give the longest life, providing any poisoning effects are absent.

The oxide cathode usually fails because it adsorbs gas and is "poisoned." One of the factors which contribute to poisoning is the gas evolved from the electrode system because of the energy dissipated. As has been shown, the cathode readily adsorbs gas, and the lower the temperature of the cathode the more readily is the gas adsorbed. The getter is present in order to cope with evolved gas, but its capacity is limited, and the valve needs only a very little of a gas such as oxygen or carbon monoxide, both of which are readily adsorbed

by the cathode coating, to poison the emission. Poisoning occurs at pressures of oxygen as low as 10^{-6} mm. of mercury, and recovery is generally impossible.

The cathode ceases to adsorb gas at about 1 000° C., but this temperature is too high from the point of view of coating evaporation. In actual practice, the cathode temperature must be adjusted to suit the type of valve. Where very little emission is required, as in a high-μ triode, and where few watts are dissipated in the anode, the operating temperature can be as low as 750° C.; but for a rectifier which requires a large emission throughout life, and in which considerable watts are developed, the temperature during life must be not less than 850° C.

One other factor influences life. The design of the heater-cathode system determines the temperature distribution along the cathode. If the temperature-difference between end and centre is great, then the ends will become poisoned, and the valve will fail because part of the cathode has been rendered useless.

(b) Mechanical Life

Apart from failure of the emission, the valve may fail because it develops a mechanical defect. One such

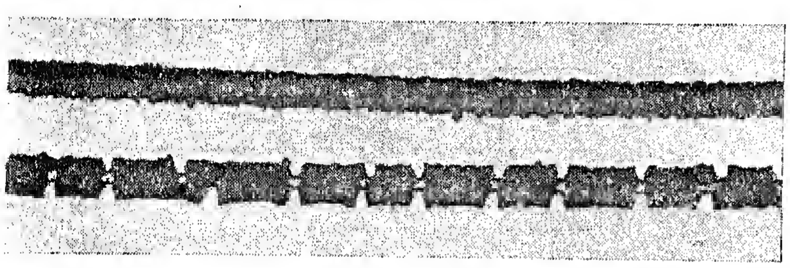


Fig. 46

form of failure is for the heater of an indirectly heated valve to fracture, particularly when it is of the hair-pin type. This is usually due to the fact that the tungsten expands and contracts much more rapidly, when the heater temperature is varied, than the insulator coating, which adheres tightly to it. The condition is particularly severe when the valve, as in practice, is switched on and off several times a day. To avoid this difficulty it is desirable for the coating, instead of forming a smooth shell, to consist rather of a series of beads. The difference in appearance is shown in Fig. 46. The effect is obtained by careful control of the initial density of the insulating material, so that the coating on the heater can shrink during sintering.

(c) Electrical Life

Other causes of failure are the development of electrical leaks, grid emission, and gas in the valve during life. No specific cure for any of these troubles can be listed, but any particular type must be treated according to the symptoms observed.

Electrical leakage may be due to volatilization of active cathode material and getter, and designs must be modified to overcome these defects. Grid emission must be looked after by suitable design of the grid cooling arrangements which have already been described. The evolution of gas during life must be studied from the point of view of the gas content of electrode materials, the pumping, and the gettering techniques. All these factors are dealt with in detail in various sections of the paper.

Where very long lives (20 000 hours and more) are required, as in valves for use in P.O. telephone repeater circuits, low-temperature operation of the cathode is essential. In order to avoid poisoning during life, the pumping schedules are lengthened to an extent quite impracticable for ordinary manufacture of valves for broadcast reception. The lengthened pumping treatments are necessary in order to ensure that practically no gas is evolved in the valve during subsequent operation.

LIMITATIONS DUE TO BACKGROUND NOISE

Since the main function of a receiving valve is to amplify signals it follows that any noise generated by the valve itself will set a limit to the maximum useful gain which can be employed.

In the early days of bright-emitter valves a phenomenon known as "crackling" was often met with. This was an intermittent effect which was ascribed to irregular emission from the hot tungsten filament. With the introduction of thoriated tungsten dull-emitter valves the filament became less ductile and was more easily excited by mechanical shock into a state of transverse vibration. In consequence the limit of amplification at that time was determined mainly by the microphonic properties of the valve.

(a) Alternating-Current Hum

When the need for the operation of receiving-valve cathodes from an alternating-current supply arose, a fresh limitation presented itself in the form of a.c. hum. Early attempts to use valves with a.c. heating of a filamentary cathode met with considerable difficulty. The first modifications were heavy-current low-voltage filaments, which avoided flicker due to temperature-changes and reduced the electrostatic control of the electron stream. Unfortunately, the heavy current produced a strong magnetic field, which set a limit to this method. Nevertheless, commercial receivers were manufactured for a time on these lines.

The functions of heater and cathode were now separated, so that the current did not flow through the cathode material. Difficulties arose due to the need for providing insulating material between heater and cathode. Vacuum insulation was of course satisfactory but required liberal dimensions, which resulted in high-consumption heaters and inefficient valves from the mutual-conductance point of view. The development of special insulating materials has been dealt with elsewhere in this paper, and it will be sufficient now to indicate the present limitations of indirectly-heated-cathode valves.

Where the heater can be operated with cathode return to the centre point of the heater supply, the main source of hum is magnetic in origin. The effect can therefore be reduced by reducing the heater current and to some extent by special arrangements of the heater. Assuming the heater watts to remain constant, the low-current method results in increased heater voltage with

a greater increase in the hum produced when the slider of the potentiometer shunting the heater is moved from the centre point. This is due to: (1) Heater ends producing a grid effect on the electrons from the end of the system. (2) Thermionic emission from the heater being collected by the grid (especially with high resistance in grid circuit). (3) Ends of heater robbing electrons from the main system, either at the ends or strays. (4) Capacitive coupling between heater leads and grid lead.

These effects are set forth quantitatively in Fig. 47. The curve for the MH4 valve shows the hum produced by the straight "hairpin" heater operated at 4 volts, 1·0 amp. Contrasted with these is an MH41 valve fitted with a heater of spiral or reverse "helix" form. The difference in hum at the ends of the potentiometer is a feature of the electrode arrangement, but the reduction in magnetic hum at the centre point is marked. The third pair, for the H30 valve, concerns a further

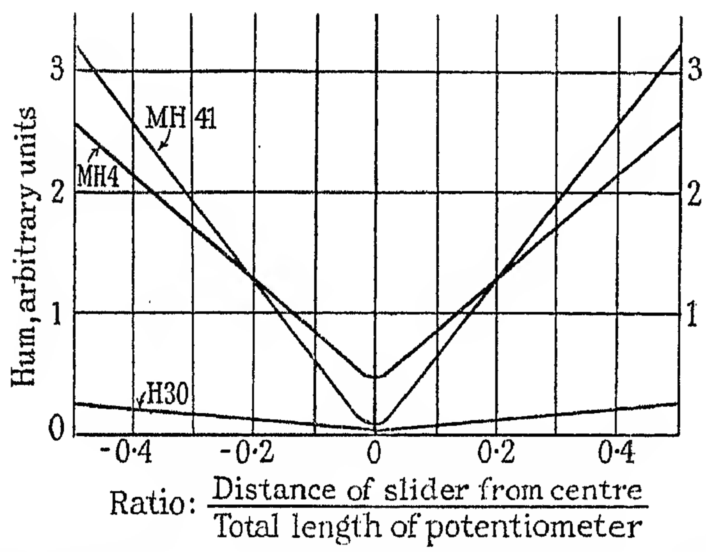


Fig. 47.—Effect on hum of various heater-cathode designs.

heater of spiral form but operating at 13 volts, 0·3 amp. Here the magnetic hum at the centre is still further reduced by the lower current, and the steep rise at the end has been minimized by taking the grid connections to the top of the bulb and by the use of screens round the heater leads.

A special case of commercial importance arose with the introduction of the d.c./a.c. set, where for the sake of economy the heaters are operated in series on an a.c. supply. It is necessary for the cathodes of all the valves to be connected to one end of the a.c. supply, so that large a.c. voltages exist between the heater and cathode in many of the valves. In this case the a.c. voltage between heater and cathode may be several times as great as the voltage across one heater. All these effects can be minimized by enclosing the ends of the heater in metallic shields connected to the cathode and by removing the grid lead as far away as possible from the heater leads.

In general, it can be said that it is now possible to make valves which, when operated on an a.c. heater supply, will give rise to a hum no greater than the basic "hiss" level arising from the shot and resistance noises. Such valves, however, demand special construction and are more expensive to manufacture than ordinary types.

While these latter effects are now well known as limitations to the amplification obtainable with valves, it is proposed to refer to them briefly.

(b) Shot Noise

The noise due to this effect arises from the random nature of the arrival of electrons as discrete particles at the surface of the anode. They generate a wide band of frequencies, and have been shown by Moullin and Ellis* to be equivalent to a mean-square voltage of approximately $11 \times 10^{-20} Idf/g_m^2$ at the grid of the valve in the case of an amplifier covering the range of audio frequencies given by df, where I = anode current (amperes) and g_m = mutual conductance (amperes per volt).

(c) Resistance Noises

In most applications of the valve it is necessary to connect a high resistance or impedance in the grid circuit. This resistance gives rise to further noises, which again cover a wide frequency band. Johnson and Nyquist† have shown that the effect of these is equivalent to a mean-square voltage of $1 \cdot 6 \times 10^{-20} Rdf$ across the resistance when the latter is measured in ohms.‡

A practical case where noises of this kind prove a serious limitation is in the application of the photoelectric cell, where a high grid resistance is imperative owing to the low currents produced by the cell. In this field the electron multiplier, described by Dr. V. K. Zworykin,§ is of particular interest. By dispensing with the need for a coupling circuit the resistance noises are eliminated, and the limiting noise becomes of the smaller order arising from shot noise due to the multiplier.

(d) Parasitic Noises

Apart from these fundamental limitations, designers are faced with more immediate problems by reason of noises of a greater magnitude which can be classed as "parasitic." In the manufacture of modern oxide-coated cathode valves it is necessary to heat the electrodes, including the cathode and heater, to high temperatures during evacuation. It is also essential to employ some form of "getter," usually in the form of a volatilized film to assist in removing occluded gases. These operations may result in the evaporation of the electrode metals, which tend to form conductive films on the materials used to support and insulate the electrodes. The cathode also will release barium metal during pumping and activation. These films may give rise to high-resistance leaks of variable effect due to the bad contacts between them and the electrode supports. Various types of "umbrella" insulators have been employed with success to obviate these effects, while careful attention to pumping technique may also yield beneficial results.

Again, it is found that noise may arise as the result of ionization in the valve. At quite low pressures, of the order of 10^{-5} mm. of mercury, these noises may easily exceed those produced by the shot and thermal effects, if a high grid resistance is used. They are, of

* See Reference (34). † *Ibid.*, (35), (36).
‡ For a complete bibliography on valve noise, see Reference (38).
§ See Reference (39).

course, of a similar nature, but are set up by the positive ions resulting from the ionization of the gas.

In the manufacture of modern receiving valves having a large number of grid electrodes with very small inter-electrode spacing, the problem of excluding foreign material is a very real one. A considerable quantity of dust and fluff is normally present in the air and this may settle on the electrodes during assembly and be sealed in with the system. During heat treatment much of this material will be carbonized and provide loose-contact short-circuits in the final valve. It will be appreciated that only one fragment of suitable shape is necessary in a valve to render it useless for normal purposes. Elaborate precautions have been found to be necessary to exclude this material.

Another parasitic effect with which all users of valves will be familiar is that of microphonic noise. This of course arises from movements of the electrodes relative to one another, resulting in slight changes in the characteristics.

In filament (battery) valves the main source of the effect is the transverse vibration of the filament wire or strip. Much has been done to limit this

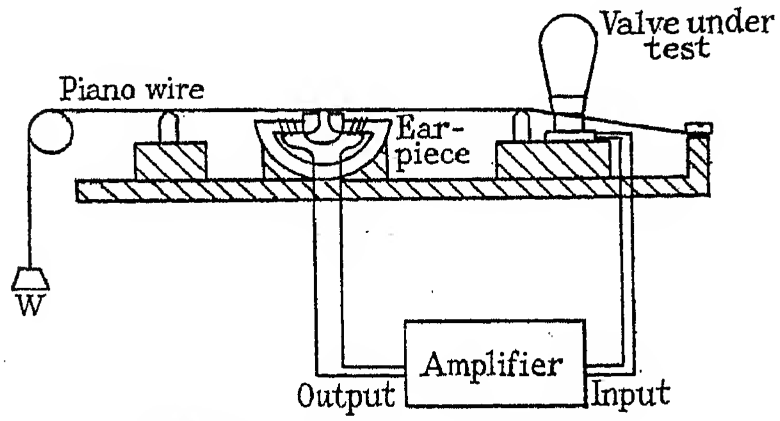


Fig. 48.—Test for microphone noise.

vibration by the use of insulated members to contact with the filament at intermediate points and so produce a damping action. Each contact of this kind, however, robs the filament of some of its heat and so limits the number which can be used. Moreover, owing to the small clearances used in modern battery valves, the insulating path is necessarily short and the difficulties of avoiding noise due to films are considerably increased.

In indirectly-heated valves the cathode is a comparatively rigid structure, and if the electrodes are well bonded at the two extremities a much lower level of microphonic response is possible than in the case of battery valves. If the gain now be increased it will be found that microphonic effects arise due to a cantilever vibration of the whole system, and improvements can be secured by reducing the flexibility and moment of inertia of the system. In general, stiffer supports, lighter and shorter systems, and reduced height of mounting, are all beneficial.

In the study of microphonic noises it has been found useful to employ the apparatus shown in Fig. 48. The valve is mounted on a platform provided with two bridges over which a steel wire passes. The output of the valve is amplified and used to actuate a magnetic earpiece which drives the steel wire. With correct phasing the system will build up to a continuous vibration whenever the wire is tuned by means of the movable bridge to the resonant frequency of any part of the electrode system. The electrodes can now be examined with a binocular microscope, when the cause of vibration will usually be apparent.

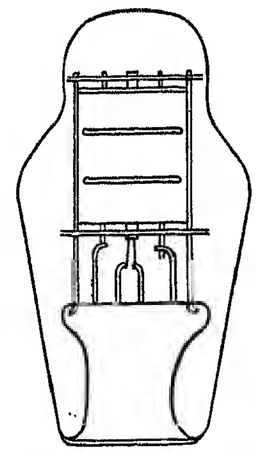


Fig. 49

ROBUSTNESS

The early users of radio valves were content to treat them as delicate articles, and manufacturers generally relied on cotton-wool methods in order to ensure safety in transit. This method was made more than ever necessary by the advent of thoriated-tungsten filaments, especially when they were carbonized or of very low current consumption.

With the general introduction of oxide-coated filaments and cathodes the emissive member ceased to be the chief factor limiting mechanical strength. Improvements were secured by bonding the electrodes by means of insulating members and by the use of thicker supports from the glass "foot" or "pinch." These changes had the unfortunate effect of increasing the difficulties of the glasswork, resulting in greater wastage in manufacture. By a choice of stiffer materials such as nichrome, magno-nickel, etc., some further improvement was secured, but it was not until the system was supported at the upper as well as the lower end that a real step forward was achieved.

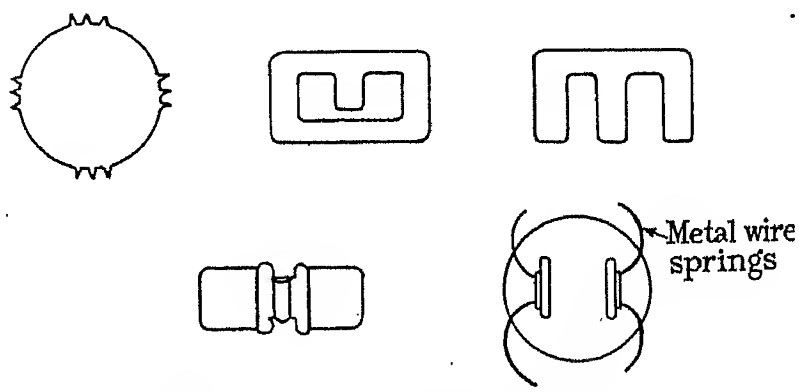


Fig. 50.—Types of locating members.

In the case of glass valves this was made possible by the use of glass bulbs with specially-shaped tops, generally known as "dome top bulbs" (see Fig. 49). Naturally there must be some variation in the internal diameter of the dome portion of these bulbs, and in consequence a great variety of methods have been used to compensate for these variations. As shown in

Fig. 50, these include various designs of flexible supports of mica and metal, and the use of serrated edges designed to break off according to the diameter of the

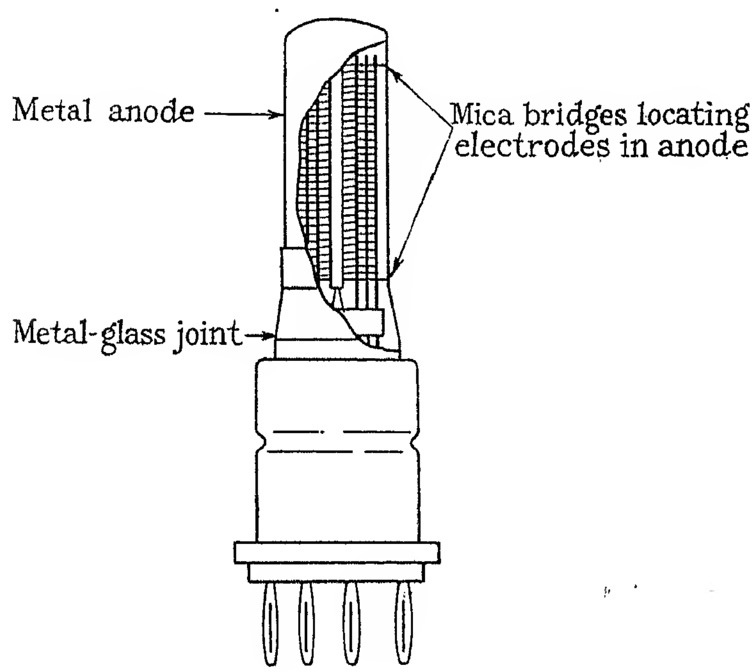


Fig. 51.—Air-cooled-anode output pentode.

bulb. In the metal-anode valves introduced in this country in 1933 (see Fig. 51) the inside of the anode became the supporting surface and, owing to the greater accuracy obtainable in a metal pressing, these devices were unnecessary.

The amplification factor (μ) of a triode valve of cylindrical form is given approximately by the equation

$$\mu = a\rho n^2 K$$

where ρ = diameter of grid wire, a = clearance between grid and anode, n = number of grid turns per unit length, and K = a constant depending on electrode form.

It is possible, therefore, to secure the same μ value by using either a heavy wire with open pitch [(*a*), Fig. 52] or a fine wire with close pitch [(*b*), Fig. 52]. In both cases the characteristics will be similar in the region of zero grid volts. As the anode voltage and grid bias are increased, however, it will be found that in the case of the heavy-wire grid a characteristic "tail" will more quickly become evident. This tail is due to a failure of the grid to control the electron stream completely, and will produce second-harmonic distortion in output triodes. This effect has been dealt with earlier in the paper.

From the point of view of the characteristic, therefore, fine grid wires are desirable, and a compromise is necessary between the mechanical and electrical requirements.

FREQUENCY LIMITATION

The maximum frequency at which a radio valve will operate is entirely controlled by the physical dimensions, configuration, and potentials, of the electrodes.

In the case of triodes used as self-oscillators the input and output capacitances are of considerable importance. Of greater importance, however, is the inductance of

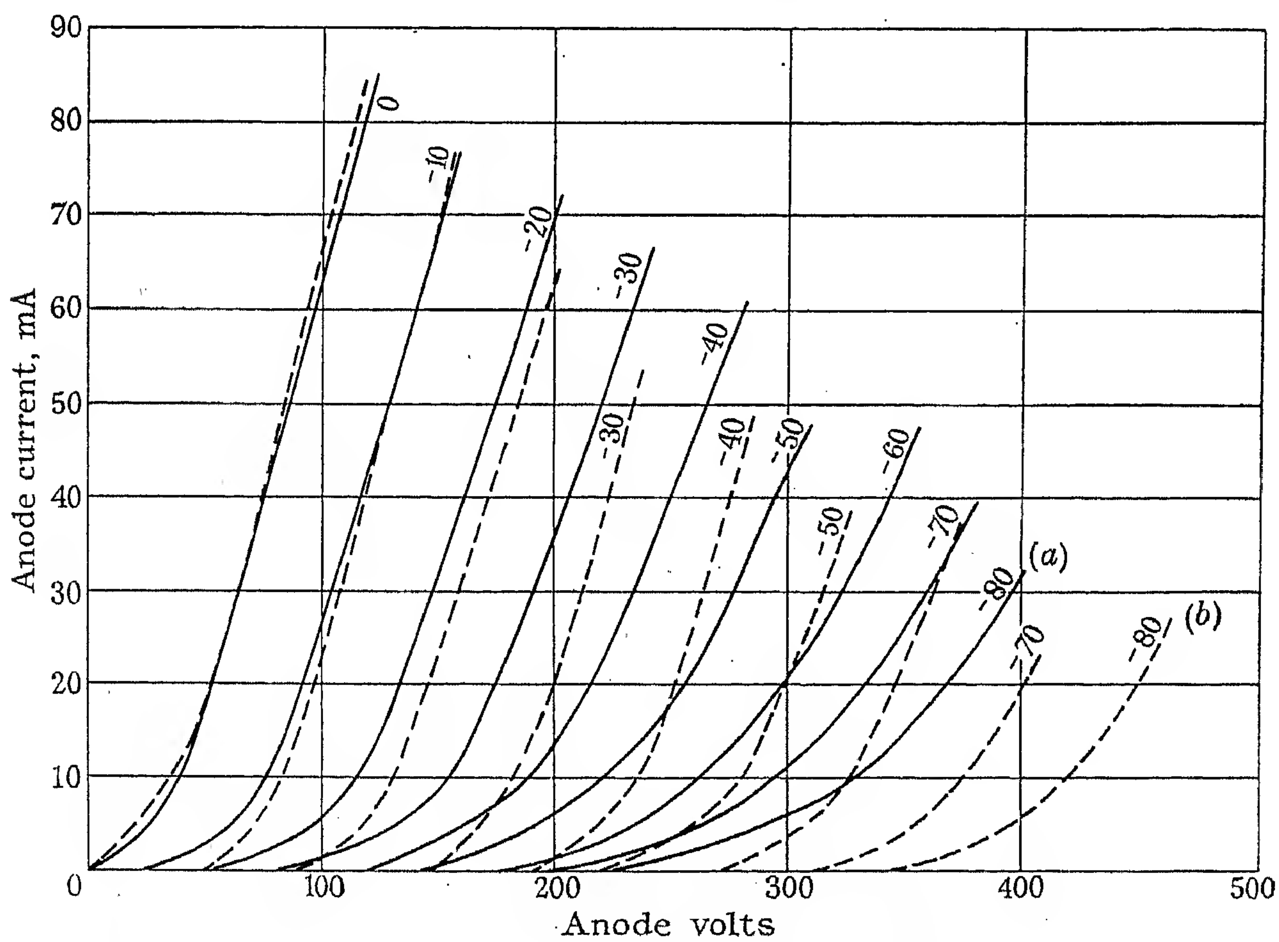


Fig. 52.—Characteristics of output triodes having grids wound with coarse and fine wires.

The strength of each individual electrode can be greatly improved by the use of heavier-gauge metals. In the case of grid electrodes, however, this tendency conflicts with the technical requirements in many cases.

the electrode leads and of the electrodes themselves. Assuming that the oscillatory circuit comprises inductance only, then the wavelength can be progressively reduced until the external circuit provides insufficient

coupling to maintain oscillation. Before this limit is reached the efficiency will necessarily fall away.

A third factor which must be taken into consideration is the "transit time" of the electrons, i.e. the time taken for each electron to pass from the filament to the anode. When the frequency becomes so high as to be comparable with the reciprocal of the transit time a lagging effect occurs which results in the production of a difference in phase between the current and the applied voltage. At the present time these factors can be overcome to some extent by the use of close clearances between electrodes, short straight leads, and small electrodes.* Wavelengths as low as 40 cm. have been reached by these methods, using conventional circuits but necessarily with very small power.

While these miniature valves or "acorns" have already been mentioned by Mr. Mullard in his Chairman's Address,† it may be of interest to give a comparison of

Table 6

	Acorn triode AH1	Receiving triode MH4
Cathode dimensions, mm.	10 × 0·63 (diam.)	25 × 2·7 × 1·3
Grid-cathode clearance, mm. ..	0·135	0·4
Grid-wire diameter, mm.	0·03	0·110
Grid-anode clearance, mm. ..	0·27	1·6
Grid-anode capacitance, $\mu\mu$F ..	1·4	4·5
Grid-cathode capacitance, $\mu\mu$F ..	1·0	7·0
Anode-cathode capacitance, $\mu\mu$F ..	0·6	5·0
Length of anode lead, mm.	15	65
Length of grid lead, mm.	15	65

their dimensions with those of a normal receiving valve (see Table 6).

The assembly and inspection of these very small valves necessitates the use of binocular microscopes at almost every stage. From the dimensional point of view the work is akin to that of the watchmaker. The latter, however, has a marked advantage over the valve manufacturer in that his component parts, though small, are individually rigid and can be machined to accurate limits. The manufacturing cost of acorn valves places them at present outside the range of commercial receiving practice, and, even if this were not the case, their life and general robustness could hardly be considered up to the present market standards.

When tetrode and pentode valves are used as amplifiers and if due precautions are taken to avoid circuit losses it will be found that the upper limit of frequency is set by self-oscillation. The inductance of the screen and/or suppressor-grid lead makes it impossible to earth these electrodes effectively. As a result a coupling arises between anode and grid, causing self-oscillation. Pentode valves in which the suppressor grid has been brought out at the cap are more limited in this respect than tetrodes, but if the suppressor grid is connected internally to the cathode the pentode is then equally efficient.

* See Reference (37). † *Ibid.*, (40).

TESTING

The testing of valves has always presented a real problem to the manufacturer, and it can now be said to be one of the most expensive items in manufacture. The number of electrical tests has grown steadily with time, while the complexity of test circuits has easily kept pace with them. There are, of course, certain tests which are common to all valves, and it will be as well to examine these briefly for the benefit of those engineers who are not directly engaged in manufacture.

(a) Filament Current or Voltage

Valves intended for parallel operation either from batteries or from a.c. supplies are checked for filament current at a fixed filament voltage. A tolerance of ± 10 per cent is customary practice, although smaller limits may be desirable in special cases.

Where the design is specifically for series operation, as in the case of a.c./d.c. valves and some repeater types, a measurement of voltage at a fixed current is, of course, more usual. Here again a tolerance of ± 10 per cent may be regarded as normal. Owing to the resistance characteristics of the filament, however, the tolerance may be equivalent to only ± 5 per cent under constant-voltage conditions.

In the case of filament valves of low current consumption the anode current may represent an appreciable portion of the filament current, and the test will need to be carefully specified.

(b) Anode Current

One of the most useful tests from the user's point of view, and also the simplest, is a measurement of anode current at some suitable working point. It has been shown earlier in this paper that the anode-current value may vary considerably even under closely-controlled manufacturing conditions. In the case of valves of considerable power dissipation, therefore, it is often good practice to adjust the grid voltage so that a predetermined anode current is obtained and to record the grid voltage as a criterion of the characteristic.

(c) Negative Grid Current

A measurement of the negative or reverse grid current is necessary in all types of modern valves, since an excess would prove objectionable in many operating circuits. In the early days it was general practice to vary the grid-bias voltage from a high negative voltage until the maximum reverse grid current was obtained (see Fig. 53). The reading so obtained was known as the "backlash." The method was objectionable, since the reading obtained depended on the positive as well as the negative grid current. To-day it is more usual to make the

measurement at a point on the straight portion of the reverse grid-current curve where positive grid current will not affect the result. If the reading is taken in

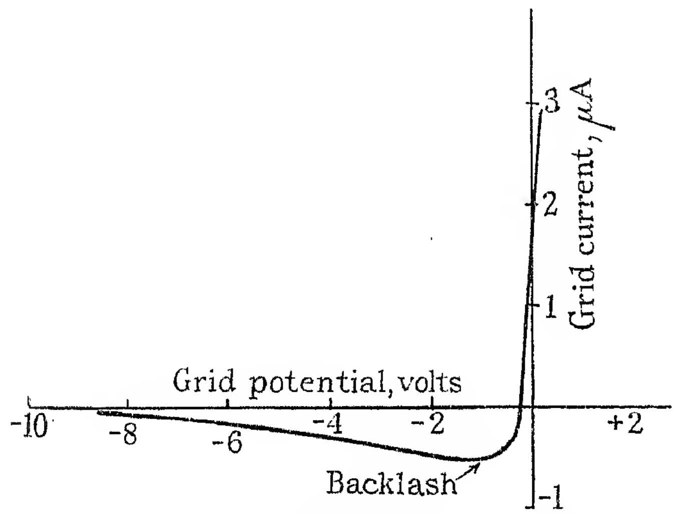


Fig. 53.—Grid-current characteristic.

this way the ratio of grid current to anode current for any given type will be proportional to the gas pressure in the valve.

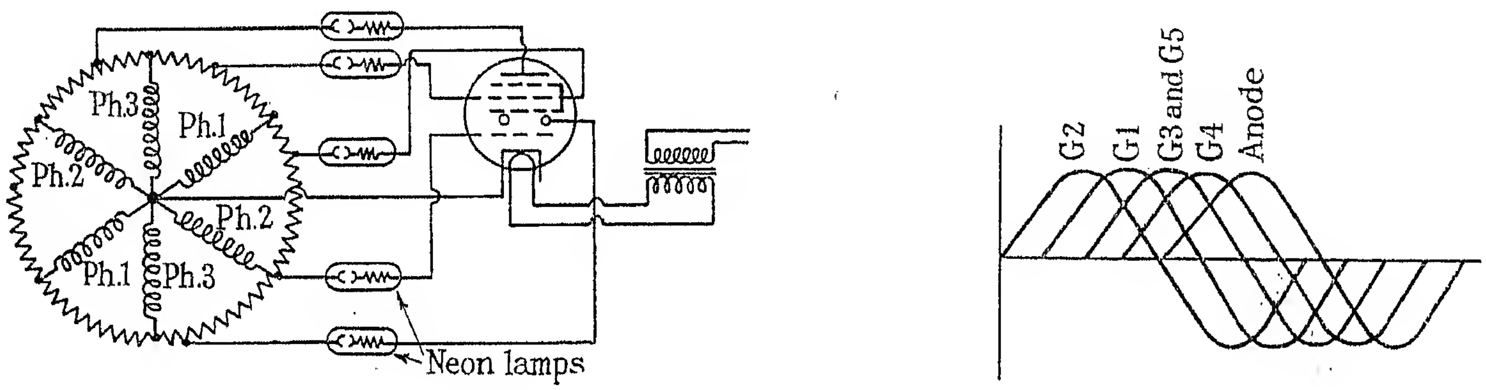
Among the useful tests which may be applied to valves of all types is one which tests for disconnections and for short-circuits between electrodes. With modern multi-electrode valves with small clearances an occasional short-circuit or broken wire will occur. Such a fault is difficult to localize on static test and may operate to delay testing or to damage meters. This test, which originated in America, makes use of a hexaphase supply connected to a ring potentiometer (see Fig. 54). The cathode of the valve is connected to the centre point of the circuit, while each electrode is taken through a suitable neon lamp to an appropriate tapping-point on the potentiometer. With the cathode hot, each neon lamp will glow on one electrode (see Fig. 54) and a disconnection will result in one or more of the neon lamps being extinguished. Should a short-circuit occur between any two electrodes the neon lamps associated with them will glow on both electrodes.

To this test must be added special tests applying to a limited number of types. In the case of amplifying valves it is necessary to measure mutual conductance at the operating point, while those types having variable-mu control must have the measurement repeated at a sufficiently high negative bias to ensure that correct "tail" characteristics are present. These measurements are best made by an a.c. method. A known a.c. voltage is applied to the control grid, and the a.c. component of the anode current is separated from the d.c. and read off directly on a suitable meter. Precautions are necessary in this test to ensure that the a.c. load impedance in the anode circuit is effectively zero.

Output pentodes and triodes are conveniently tested for power output by a similar method using a resistive anode load of the correct value for the particular type. In this case, however, the grid swing applied must cover the full operating range.

Types of amplifying valve with "straight" characteristics are normally tested for "cut off" to ensure that no undesirable characteristic tail is present. This test is usually made at a fixed negative grid-bias, and a maximum limit for anode current is set. Such a test is particularly desirable with types used for anode-bend detection.

Heptode frequency-changer valves must, of course, be tested for conversion conductance, and there are two excellent methods available. The first, a low-frequency test, can be made on the 50-cycle supply. It consists in supplying the oscillator grid with its appropriate peak voltage via a grid leak and condenser of suitable value (see Fig. 55). An a.c. voltage of the same frequency, but of small amplitude (say, 1 volt), is simultaneously applied to the signal grid, and the d.c. anode current is recorded on a moving-coil meter. The signal-grid voltage is now reversed in phase and the anode current again recorded. The difference between the two readings expressed in milliamps., divided by twice



(a) (b)

Fig. 54.—Short-circuit and open-circuit test.

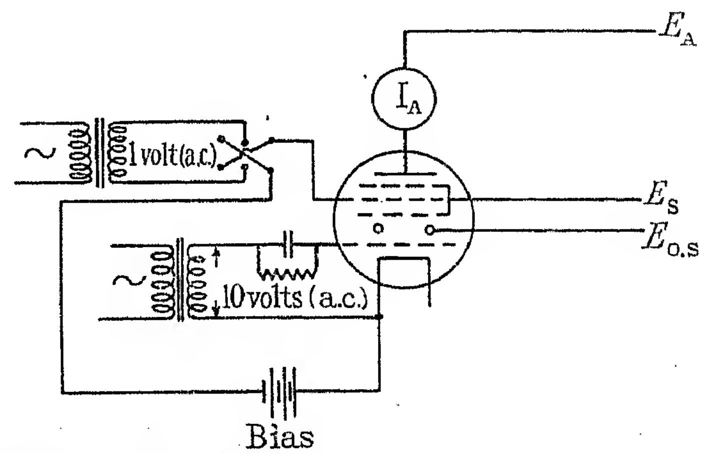


Fig. 55.—Conversion conductance test for heptode valves.

the peak voltage applied to the signal grid in volts, gives an accurate value for the conversion conductance. A separate oscillatory test at high frequency is necessary for the triode section.

The second method, which is more rapid in use, is carried out at high frequency. In this case the oscillator section is connected to a suitable circuit so that it may generate its own appropriate peak voltage. A known signal voltage of appropriate frequency is applied to the signal grid, and the resulting intermediate-frequency signal in the anode circuit is recorded directly by means of a valve voltmeter. This method, though more rapid than the low-frequency test, suffers from the disadvantage that it is not absolute and frequent calibration is necessary.

One of the most difficult requirements to meet in modern valves is that of freedom from noise. The noise test needs to be included in the tests made in the producing department, in order that quick action may be taken when rejects occur. The most suitable test is that made in a receiver of the type most usually employed for the particular valve under test, and precautions are necessary to avoid the interference always present in a valve factory. To this end the whole receiver chassis may be enclosed in an earthed metal box with the one test position brought outside with screened leads. This enables the valve to be handled and to be subjected to tapping in order to indicate any looseness in the system.

As a precautionary measure it has been found desirable for many years to repeat the tests, including the noise or " chassis " test, on all valves before despatch. This second test eliminates any cases of slow air leak which may occur, and also provides a check on general accuracy. To avoid disputes over borderline cases the section or factory limits are best set to a slightly narrower tolerance than those used on final inspection.

No modern valve factory would be complete without a very complete equipment for life test. Such tests call for a very rigid routine to ensure that all types are tested as soon as possible after manufacture, while the racks used must be flexible in order to deal with new valve types and altered conditions for existing types. The collection of life-test valves is best carried out under separate control, divorced from actual manufacture, and however small the quantity made a certain minimum number should be tested each week. When manufacture is carried out in large numbers a percentage, varied on a sliding scale, is desirable.

FUTURE DEVELOPMENTS

In considering what may be the future developments in radio receiving valves it is useful to review the tendency in past years. In this country the main effort of most manufacturers has been to secure the greatest possible degree of efficiency from each valve. This policy, dictated by competition, has resulted in the frequent introduction of new types and a general lack of standardization between the products of various manufacturers. Such competition has made the attainment of economical and accurate production difficult, and, moreover, the short active life of individual types hindered the study and correction of faults arising in service. During the last year or two there has been some abatement in the rush of new types and a more intensive concentration by manufacturers on such factors as reliability, uniformity, and economy.

As improvements in materials and technique become available it is usually possible to employ them either to secure higher levels of characteristic or to increase the economy of the product at the standard of performance existing at the time. From present indications it would appear that both these lines of attack are likely to continue to be followed. At the present time the radio industry in this country would appear to be entering a period of more intensive competition than ever before, and manufacturers will strive to secure the best value of performance for a given cost while retaining a satisfactory level of reliability and uniformity.

It would appear that there is still room for improvement in valves used for the shorter wavelengths, particularly in the region between 6 and 8 metres, which is now of such interest for television purposes. One of the items outstanding in this direction and which is receiving much attention at the present time is the frequency-changer.

Existing frequency-changers, particularly those of the triode hexode type, will operate reasonably well down to 5 or 6 metres if precautions are taken in the circuit layout to avoid undue inter-circuit coupling. Operation down to 3 metres may, however, become necessary if a number of television transmitters have to be accommodated in a restricted area.

A further item of considerable interest at the present time is the provision of valves suitable for wide-band amplifiers. The present tendency is to employ high-frequency pentode valves in which the ratio of mutual conductance to input and output capacitances is as great as possible. By reason of the low impedance of the anode load, usually employed to obtain the wide frequency coverage, the grid-anode leakage capacitance of the valve is of much less importance than in valves used with high-impedance tuned circuits, and may be allowed to rise to a value approaching 100 times the figure usually necessary in the latter types.

A practical instance of this is given by the N43 valve. This is a development of the high-slope output pentode type N41, and has been fitted with earthed screens at the ends of the system and a top grid-connection to reduce the leakage capacitance between anode and grid (Fig. 26 and Fig. 43, Plate 2). This treatment has not resulted in any appreciable loss of mutual conductance but has reduced the grid-anode capacitance from more than 1 $\mu\mu$F to the neighbourhood of $0 \cdot 2$ $\mu\mu$F. While this latter figure is very high by comparison with that for normal high-frequency pentodes, it is yet low enough for the wide-band type of amplifier.

In considering future developments in radio receiving valves mention must be made of the possibilities of the use of secondary emission. Practical demonstration has already been given of a secondary-emission multiplier operating from a light source and giving a marked improvement in signal/noise ratio. It seems probable, however, that if a grid electrode were introduced before the first collector, so that normal amplification became possible, the advantages in respect of noise would disappear. Such an arrangement would make possible a

very high order of amplification in a very small space and would offer many advantages in the rather limited field of high-gain amplifiers. In radio receivers of to-day, however, and particularly in the superheterodyne receiver, valves are used to secure selectivity as well as amplification, and it is very difficult to imagine a single multiplier which would replace the functions of the high-frequency amplifier, frequency-changer, intermediate-frequency amplifier, second detector, and low-frequency amplifier.

The science of electron optics has been studied for many years and is essential to the design of cathode-ray devices. It is only quite recently, however, that serious attention has been given to the design of amplifying devices based on the principle of deflecting a beam of electrons rather than controlling the intensity of an electron stream, and up to the present there have been no outstanding developments along these lines, except in very specialized cases.

Many advances in valve efficiency have in the past been brought about by improvements in the emission efficiency of the cathode. It is the view of the authors that the oxide cathode has to-day reached a very high plane, and it is unlikely that any major improvement will be realized in this direction. Caesium cathodes, which have been referred to elsewhere in this paper, have been carefully explored by many investigators; although under certain limited conditions of use they may give much greater efficiency than the oxide type, there would appear to be no immediate prospect of their use in practical radio valves.

In conclusion, the authors desire to tender their acknowledgments to the General Electric Company and the Marconiphone Company, whose research work on valves has inspired this review.

REFERENCES

(1) British Patent No. 145421—1916.
(2) W. Schottky: *Archiv für Elektrotechnik*, 1919, vol. 8, p. 299.
(3) A. W. Hull and N. H. Williams: *Physical Review*, 1926, vol. 27, p. 432.
(4) A. W. Hull: *ibid.*, 1926, vol. 27, p. 439.
(5) British Patent No. 287958—1926.
(6) S. Ballantine and H. A. Snow: *Proceedings of the Institute of Radio Engineers*, 1930, vol. 18, p. 2102.
(7) I. Langmuir: *Physical Review*, 1913, vol. 2, p. 450; *ibid.*, 1923, vol. 22, p. 347.
(8) W. H. Aldous: *Wireless Engineer*, 1936, vol. 13, p. 576.
(9) W. Schottky: *Physikalische Zeitschrift*, 1914, vol. 15, p. 526.
(10) T. C. Fry: *Physical Review*, 1921, vol. 17, p. 441.
(11) I. Langmuir: *ibid.*, 1923, vol. 21, p. 419.
(12) F. B. Vogdes and F. R. Elder: *ibid.*, 1924, vol. 24, p. 683.
(13) H. J. Van der Bijl: *Verhandlungen den Deutschen Physikalischen Gesellschaft*, 1913, vol. 15, p. 338; *Physical Review*, 1918, vol. 12, p. 180.
(14) British Patent No. 423932—1933.
(15) H. Rothe and W. Kleen: *Telefunken Röhre*, 1936, vol. 6, p. 1.
(16) J. C. Warner, E. W. Ritter, and D. F. Schmit: *Proceedings of the Institute of Radio Engineers*, 1932, vol. 20, p. 1247.
(17) L. R. G. Treloar: *Nature*, 1936, vol. 137, p. 579.
(18) G. F. Metcalf and B. J. Thompson: *Physical Review*, 1930, vol. 36, p. 1489.
(19) G. W. Warren: *G.E.C. Journal*, 1935, vol. 6, p. 2.
(20) C. J. Smithells and C. E. Ransley: *Proceedings of the Royal Society*, A, 1936, vol. 155, p. 195.
(21) I. Langmuir: *Physical Review*, 1923, vol. 22, p. 357.
(22) A. L. Reimann: " Thermionic Emission " (Chapman and Hall, 1934).
(23) S. Dushman: "Reviews of Modern Physics," vol. 1 (1930).
(24) I. Langmuir and K. H. Kingdon: *Physical Review*, 1923, vol. 21, p. 381.
(25) I. Langmuir and K. H. Kingdon: *ibid.*, 1924, vol. 23, p. 112.
(26) J. A. Becker: *ibid.*, 1926, vol. 28, p. 341.
(27) K. H. Kingdon: *ibid.*, 1924, vol. 24, p. 510.
(28) A. Wehnelt: *Annalen der Physik*, 1904, vol. 14, p. 425.
(29) M. Benjamin and H. P. Rooksby: *Philosophical Magazine*, 1933, vol. 15, p. 810.
(30) M. Benjamin and H. P. Rooksby: *ibid.*, 1933, vol. 16, p. 519.
(31) E. Patai and Z. Tomaschek: *Kolloid. Zeitschrift*, 1936, vol. 74, p. 3.
(32) M. Benjamin: *Philosophical Magazine*, 1935, vol. 20, p. 1.
(33) A. L. Reimann: *ibid.*, 1934, vol. 18, p. 1117.
(34) E. B. Moullin and H. D. M. Ellis: *Journal I.E.E.*, 1934, vol. 74, p. 323.
(35) J. B. Johnson: *Physical Review*, 1928, vol. 32, p. 97.
(36) H. Nyquist: *ibid.*, 1928, vol. 32, p. 110.
(37) B. J. Thompson and G. M. Rose: *Proceedings of the Institute of Radio Engineers*, 1933, vol. 21, p. 1707.
(38) J. B. Johnson and F. B. Llewellyn: *Transactions of the American I.E.E.*, 1934, vol. 53, p. 1449.
(39) V. K. Zworykin: *Journal I.E.E.*, 1936, vol. 79, p. 1.
(40) S. R. Mullard: *ibid.*, 1935, vol. 76, p. 10.

[The discussion on this paper will be found on page 432.]

DISCUSSION BEFORE THE WIRELESS SECTION, 2ND DECEMBER, 1936

Mr. L. B. Turner: The history of the thermionic valve seems to divide itself into five main epochs. There are the four great successive jumps associated with the names of Edison, Fleming, de Forest, and Langmuir; and there is the fifth period of minute and intricate development. Of this last period the authors have given a delightful survey. If any of us have been disposed—as I think I have—to regard the really important work as finished a quarter of a century ago, we were clearly mistaken. The modern valve is not the old valve with a patch of lime on the cathode, and an additional grid inserted from time to time by a clever glassblower.

On page 403 the term *Inselbildung*, literally "island formation," is (as I think) used rather misleadingly. *Inselbildung* is not *due to* the non-uniformity of electric field; it *is* that non-uniformity. The word is merely a picturesque description, in German, of the obvious condition of field close to the region immediately below a wire of a grid whose potential is negative. There is obviously no emission from a portion of cathode situated there. In general I deprecate the construction of cant terms in wireless literature by the importing of homely foreign words, unless, of course, some gain in clarity results. More familiar examples are the words *ziehen* and *Litz*. It is right in German—but not, I hold, in English—to describe the pulling into step of one oscillator by another as *ziehen*; for *ziehen* simply means "to pull." Again, *Litzdraht* is stranded wire; but why should an Englishman write *Litz*, especially when it is not the stranding, but the separate insulation of the strands, which he wishes to express? This use of *Litz* is on a par with the comic term *bobbine de self*, wherewith a Frenchman thinks he expresses the gist of "self-inductance coil." We in England, knowing the language, prefer the abbreviation, "inductance coil."

Finally, I want to ask the authors for a little more information about the rectilinearity of valve characteristics. In the simple triode, with no complications from secondary emission and with the whole cathode emission passing to the anode, the concave curve of the $\frac{3}{2}$-power law is not merely given a point of inflection as an obvious effect of gradual saturation and so on. Somehow, to a degree that has always puzzled me, the valve maker often provides a magnificent extent of straight line between concavity and convexity. I want to ask the authors whether this is fortuitous; or whether the valve maker strives, empirically or by calculation, to emphasize this feature; and, if so, how he does it.

In the more complicated multi-grid valves, I suppose that grid currents, and especially secondary emissions, largely influence the shapes of the characteristics. A useful valve would be one with two control grids, each of which shows substantially constant transconductance, of value dependent on the potential of the other. Expressed otherwise, if i is the anode current, and e_1, e_2 are the grid potentials, a useful portion of the i/e_1 characteristic is straight—with a slope linearly dependent on e_2. I have encountered only one valve (the Mullard octode FH4) which approaches this condition. I mention the matter in the hope that the authors may be tempted to make some comment on it.

Dr. A. C. Bartlett: I agree with Mr. Turner on the subject of the word *Inselbildung*; I have tried it on quite a number of wireless engineers and I have not found one who knows what it means. Turning to another point of nomenclature, the authors refer to "contaminated-metal emitters." In modern English, "contamination" means that something bad has become mixed up with something good, and that the result is bad. In the case of these so-called contaminated-metal emitters, on the other hand, the thorium is added to the tungsten with great care and the result is good; so that I think "contamination" is not the right word to use. In this same connection the authors mention the use of phosphorus; is not phosphorus used only with the pure tungsten filament? I believe it was the use of magnesium as a getter which made the thoriated tungsten filament a real commercial success.

I am disappointed to find that on page 417 the vapour process is not fully described.

The authors have not yet found a sovereign cure for grid emission, and they still lack full control over screen emission. This fact might serve as an excellent challenge to the other valve-makers to say what they have done in these two fields.

It is interesting to find that the authors do not expect further large-scale progress in the oxide-coated cathode, because most of the valve developments have been due to oxide-cathode progress; for instance, the modern heptodes and hexodes could not be made with the old-type tungsten filament. It is interesting to speculate in what direction progress is to be looked for. If, as the authors say, there is going to be a vast amount of competition between the valve-makers, it would be a very good thing for set-makers, and also for all users of valves, if the valve-makers concentrated their attention on reducing the $\pm$ 40 per cent variation in characteristic, and did not worry so much about getting big increases in conductance. The other developments indicated seem to be in the direction of shorter waves. The authors mention 5 and 6 metres for television, but I understand that American engineers have a television transmitter working at 1·7 metres. In this connection the authors show an acorn valve, and it would be interesting to know what they think of this type, and whether they are going to produce it commercially.

Mr. T. E. Goldup: In referring to screen-grid valves the authors say: "The principal requirement in these valves is that the screen shall reduce the capacitance between anode and control grid to a very low value (0·0001–0·001 $\mu\mu$F)." Should not these figures be 0·001 and 0·01 $\mu\mu$F respectively? We are accustomed in these days to capacitances of the order of 0·003 to 0·005 $\mu\mu$F for valves of this type, and figures below these values are difficult of attainment. Fig. 6 shows a curve of the energy of primary electrons plotted against secondary-emission coefficients, and I should like to ask how one can interpret this in terms of the number of secondary electrons per primary electron. Have the authors any information on the effect of the angle of incidence of various electrodes subjected to primary electron bombardment?

They make reference to the expense involved in valve testing. In the case of the more popular types made in large quantities consistently, I would suggest that it is quite legitimate in the present state of the manufacturing art to test only a very small percentage for complete characteristics, and so control the manufacture from this point of view, and to test the bulk in some simple way giving a measure of actual performance under working conditions. In this way the expense of testing can be kept down to a minimum.

On page 430 there appears the remark: "In this country the main effort of most manufacturers has been to secure the greatest possible degree of efficiency from each valve." Presumably this means that they have arrived at the highest possible conductance. If this is at the expense of other characteristics such as input capacitance, or of valve reliability, then I think it is a most unwise policy. All set designers would like the maximum conductance in any given valve, but there are limits beyond which it becomes impossible for an increase in conductance to result in a comparable increase in gain, conversion or output as the case may be, as this limitation is usually determined by circuit considerations.

The one case where we could with advantage utilize very high conductances is in vision receivers, where, however, we also require the minimum grid-anode capacitance. These two requirements are so linked up with valve design that with our present manufacturing methods a compromise has to be effected.

I am rather worried by the authors' reference to the effect of intensive competition on valve types. There is really no need for the present increase year by year in the number of types of valves; those at present on the market can meet all the application needs likely to arise in connection with broadcast receivers and other valve applications. I would ask valve users to encourage manufacturers to settle down to standard manufacture, which I think will be reflected, as far as the user is concerned, in the price which has ultimately to be paid.

Mr. Harold S. Walker: In a broadcast system there is a large number of valves in cascade, and the problem is therefore quite different from that which confronts the designer of a receiving set. Until a few years ago, the highest required gain in a broadcast amplifier was of the order of 60 db. To-day that gain has been increased to 90 db, and the tendency is for the required amplification to increase to meet the new microphone technique which is at present being employed. Whereas the designer of a receiving set seldom requires voltage amplification greater than about 30 db, the designer of a broadcast amplifier must have valves which have a very low level of noise and microphonicity to meet his much more difficult requirements. We discovered some years ago that the valves which were the most microphonic were as a general rule those which had the lowest level of background noise. I refer in particular to valves such as the LS5 and LS7, which had their insulators completely outside the electron stream. In order to reduce the microphonicity, insulators were brought much nearer to the cathode and mica was used instead of glass. As soon as this was done valve noises began to arise, although the microphonicity was greatly improved. Generally the noise was negligible when the valve was new, but became rapidly worse after a few hundred hours of life. As the authors state, this may in some cases be due to leakage across the insulators, but we hold the theory that a good deal of the noise is due to the insulator itself emitting secondary electrons while under continuous bombardment of primary electrons from the cathode. Accordingly, some years ago we developed, in co-operation with the authors, some valves having steatite insulators, which do not emit secondary electrons, and considerable improvements have resulted from this development. There are probably other ways of getting round the difficulty; for example, I suggest that it is possible to screen the insulators from the electron stream. This might enable mica to be used as an insulator (which is very desirable from the manufacturing point of view), without its attendant troubles due to noise, the great point being to design a valve which not only is quiet at the beginning of its life but remains quiet through several thousand hours of use.

I should like to suggest to the authors and their associates that there should be a little more standardization, particularly in heater voltages and currents. Some years ago we managed to standardize 4 volts for the filaments of valves, particularly those of the indirectly heated type, but in the case of valves recently designed for series running there appears to be no standardization; some manufacturers produce valves taking 0·1 ampere, some 0·25 ampere, others 0·3 ampere, and so on. If we, as the users of valves, agree not to ask the manufacturers for any more complicated types or higher conductances, then they themselves might agree upon a greater degree of standardization in this direction at least.

With regard to the future designs of valves, it is felt that the grid should always be brought out at the top of the valve where there is a choice between bringing out the anode or the grid, and in some triodes, particularly those to be used with alternating current on the heaters, the grid should always be brought out at the top. This practice has many advantages which are well known.

It is not very difficult in these days to introduce the feed-back principle, and this is particularly applicable to the output stage of a receiver or amplifier, particularly those of the better type. By this means it is possible to reduce the harmonic content of the output stage very considerably, and this suggestion opens up a field for the better use of pentode output valves. I also think that the present output triodes could be improved, and suggest to the authors that there is a demand for an indirectly heated triode working on a high anode voltage.

I must join issue with the authors in regard to their symbols for indicating the parameters of valves. The following symbols have been standardized in this country: Amplification factor, μ; anode impedance, r_a; mutual conductance g_m. It would, I think be particularly desirable to use these national symbols more extensively.

Dr. K. R. Sturley: The authors give 0·5 megohm as the impedance of a coil working at 1 000 to 1 500 kc; surely 0·1 to 0·15 megohm would be a more correct value for the majority of broadcast receivers. They also

refer to the discovery of thermionic emission from the electric lamp. In this connection it is of interest to note that, 10 years before Edison observed the effect, Guthrie described* how he had taken a charged ball heated to dull red heat, and found that it discharged a negatively-charged electroscope, and how if it was heated to bright red heat it discharged a positively- or negatively-charged electroscope. This indicated the presence of positive ions and electrons. Other valve manufacturers have observed the poisoning effect of putting a positive voltage between cathode and heater. My own experience indicated a tendency, in certain valves, to drift back to the original conditions; the improvement was not always maintained. Furthermore, the sudden application of a d.c. voltage resulted in a large leakage value which was very quickly reduced to normal. This suggests that from an alternating-current point of view leakage may not be the same as from a direct-current point of view, and it is necessary to be careful in assessing the leakage in terms of d.c. voltage.

I am particularly interested in the question of hum, and agree with the authors' description of how hum is produced. I have noticed, however, that the most unpleasant form of hum seems to occur when the grid is negative with respect to the heater (which does not mean that it is necessarily negative with respect to the cathode). This effect is probably due to positive ions. Examination on the cathode-ray oscillograph showed a very decided peak in the 50-cycle wave just on the peak of the negative half-cycle. Another source of hum was rectification between heater and cathode, and this was particularly unpleasant in frequency-changers using cathode injection. The high-frequency voltage of the cathode circuit and the a.c. voltage between cathode and heater are in series, and the heater acts as a detector producing modulation of the high-frequency wave by the 50-cycle supply. This effect can be eliminated by connecting a condenser of $0 \cdot 001\ \mu F$ between heater and cathode. A further effect, not referred to in the paper, which I have noticed, is modulation of a tuned circuit in the grid of a valve. This is presumably due to magnetic control of the space charge by the heater current.

The authors suggest that the greatest difficulties are microphony, leakage, and inter-electrode capacitance in the "pinch," and they refer in that connection to the ring seal. I should be interested to know whether there is a possibility of the use of the ring seal being explored. The present form of pinch has been in operation at least since the end of the War, and has not progressed very far.

The paper would have been more complete had the authors referred to developments beyond the confines of this country. There have been considerable improvements, for example, in American practice; there is the American beam valve and the all-metal valve. There is also a Danish valve which operates on the cathode-ray principle.

Mr. F. D. Goodchild: With reference to the paragraph in the paper on oxide emitters, I think it was in 1914, not 1920, when oxide-coated filaments were first applied commercially; valves having oxide-coated filaments were used by the Bell system in their repeater circuits in 1914, and numbers of valves with such filaments were made during the War years in the United States. In view of the rapid rate of progress in the radio industry, it is surprising that it was not until the later 'twenties that the use of oxide-coated filaments—a simple device—became general. The delay is probably due to the large amount of attention which was given to thoriated tungsten filaments.

Fig. 46 shows the heaters used in indirectly-heated cathode tubes; it seems to me that with so much of the core exposed the tungsten must reach an elevated temperature and so increase the danger of recrystallization. In broadcast receivers designed for use on either a.c. or d.c. supplies the rectifier heater has to be designed to withstand a peak approaching 700 volts, in which case it seems to me that the exposed core is not satisfactory. This heating can be practically eliminated by the use of a coating material which has been pre-shrunk to a maximum possible density before applying it to the wire, and then applying it in 10 or 12 coats, each coat being sintered at 1 800° C. after it is applied. I have found that it is not sufficient merely to test the heater in a circuit which switches the current on and off several times a day. Some heater failures in radio receivers are undoubtedly due to mechanical vibration coming from the loud-speaker. I therefore mount indirectly-heated valves on panels of sheet iron in the centre of which is an electromagnet, fed from a beat-frequency oscillator, whose frequency is continuously varied through the audible range. This system has caused the failure of valves which have successfully withstood the switching test for many months.

Dr. R. L. Smith-Rose: It is gratifying to learn from this paper that a certain amount of fundamental research on the development of valves is being conducted in the works and research laboratories of the country, because from time to time one hears the question raised as to whether the whole of modern valve development work is not taking place abroad, and this thought crossed my mind on reading the earlier portion of the paper. Looking back over the history of the valve, it appears that, although Fleming produced the first diode, the third electrode was introduced in America, the fourth in Germany, and the fifth in Holland. There is thus some basis for the suggestion that this country is not holding its own in this type of valve research, and this feeling is confirmed on looking through the References given at the end of the paper. I take it that these comprise a typical selection of papers dealing with the development of valves. Of the 42 references given, 30 are to work that has been published in foreign journals or to British patents taken out by non-British patentees. Of the remaining 12 publications, 9 emanate from the General Electric Company's laboratory! It may be, however, that there is a good deal of research going on in this country which is not published and may not be suitable for publication.

As a result of reading this paper I now have a good deal more respect for the manufacturer than I had before. I had not realized, for example, the great importance of such accurate dimensioning of the valve as is indicated on page 410. I am appalled by the possible necessity

* *Philosophical Magazine*, 1873, vol. 46, p. 257.

of having to maintain an accuracy of 1 per cent in the dimensions of the "acorn" valve.

I endorse Mr. Turner's remarks on the question of nomenclature. It seems that we have to import from abroad not only the valves but the terms with which to describe their operation! It should not be beyond the ingenuity of those carrying out research to produce British counterparts of these foreign expressions.

I should like to inquire as to the present position regarding the metal type of receiving valve, because this was one of the cases where this country took a lead. I am thinking of the "Catkin," which came out at quite an early date but for some reason did not seem to reach the commercial stage satisfactorily. Since then such valves have been produced on a commercial scale in America.

The final suggestion that I have to make refers to future development, and is that there is a big and growing demand for better valves for use on ultra-short wavelengths. The acorn valve is not necessarily the final solution, and it is not necessary to resort to such a form of construction for wavelengths down to 1·5 or 2 m. There is a demand for a valve with a good performance on normal ultra-short wavelengths of between 2 and 10 m. It is very desirable that manufacturers should give their attention to the study of such problems.

Mr. E. B. Moullin: On page 406 the authors say: "Most of the secondary electrons possess low initial velocities. . . ." Does "low" mean "small compared with the initial velocities to which we are accustomed from a cathode"? I have been able to find little information on this subject, except in one paper by Barber* and another by Sharman;† and according to these writers the most probable velocity is usually of the order of about 4 volts, which is very high indeed compared with the 0·1 or 0·2 volt which we associate with a hot cathode. I should like to see some specific information about these velocities included in the present paper; this would complete the information given in Fig. 6.

Mr. J. P. Harvey: With regard to the measurement of the conversion conductance of pentagrids, the authors state that there are two methods, the low-frequency (50-cycle) a.c. method and the high-frequency method, and they seem to imply that the latter is not quite so accurate as the former. I should like to have their comments on this point, and also any remarks they care to make on the theory of the low-frequency method which they put forward; it does not seem to line up with the high-frequency method of measurement.

Mr. A. J. Gill: I am rather disappointed that so little reference is made in the paper to the subject of valve life. On page 424, under "Electrical Life," the authors say: "Where very long lives (20 000 hours and more) are required, as in valves for use in P.O. telephone repeater circuits, low-temperature operation of the cathode is essential." Not much is said about the possibility of increased life for the ordinary wireless valve, a matter of greatly increasing importance at the present time. In actual practice, we find that some of these valves may have an efficient emission life of anything from 100 hours to 2 000 or 4 000 hours. A commercial wireless receiver may have as many as 30 valves in it, and if each lasts 100 hours it will be necessary to replace each valve 87 times in the year, so that over 2 000 valves will have to be replaced on that receiver every year, which at 10s. each means over £1 000 a year. On the other hand, if one can get a life of 1 000 hours the cost of valve replacements will be about £100 a year. The annual cost of runnning a commercial wireless receiver on a 24-hours-per-day basis lies between £100 and £1 000. One would therefore very much like to see an improved life for some of these valves.

Another point is that the ordinary broadcast receiver has hitherto generally employed 3 or 4 valves, but now television receivers are being introduced having up to 20 or even 30 valves. Although these receivers are not used for many hours each day, the valve consumption may be fairly high, while the cost of locating and remedying the fault greatly exceeds the valve cost. I think the valve manufacturers ought to supply a valve which will last as long as the wireless set; there is no reason why it should not be built into the set.

Finally, I think there are only two voltages which should be standardized: 4 volts and 240 volts. It is time an ordinary valve was made in this country to run off the electric light mains.

Mr. B. Drake (*communicated*): I think it is generally admitted that equations (3) and (4) on page 403 are too complicated for general use. Apart from this, these equations only apply to a cylindrical system of electrodes. In practice no modern triode or multi-grid valve can be assumed to be a cylindrical system as the backbone wires supporting the grids prevent the electrons from radiating out in all directions, and, in fact, tend to focus them into two streams at right angles to the plane containing the support wires, as shown in Fig. 8 (page 406). Again, if the turns of the grid helix are closed up so that they actually touch one another, then $n = 1/\rho$, and according to (4) the value of μ, although large, will still be finite, whereas it should actually become infinite, because there now remain no spaces between the turns through which the anode field may penetrate to the grid-cathode space.

In view of the foregoing I have searched for an empirical formula which can be worked out with a slide rule and will give results in fair agreement with actual values found in practice. Such a formula is given below:—

$$\mu = \frac{50}{k} \cdot \frac{s\rho}{P^2 - \rho^2}$$

where s = grid-to-anode distance; ρ = grid-wire diameter; P = pitch of grid helix; and k = spread factor. The factor k depends upon the amount the beam of electrons spreads out between grid and anode. With flat electrodes the beam is straight and $k = 1$, but with cylindrical electrodes the beam usually spreads out and k is greater than unity. When ρ^2 is small compared with P^2 the formula becomes of the type given at the top of page 427, this form being particularly useful for adjusting the grid pitch in order to make small corrections to the amplification factor. Table A gives a comparison of values of μ calculated from the above formula (assuming $k = 1$) against actual values. The

* *Physical Review*, 1921, vol. 17, p. 322.
† *Proceedings of the Cambridge Philosophical Society*, 1927, vol. 23, pp. 523, 922.

agreement is quite good except for the HL2 valve, in which the central part of the filament is held close to the grid backbone supporting wires by insulated hooks, and for the A537, in which the calculated value is high owing to the spreading-out of the electron beam.

The loss of mutual conductance at wide grid pitches (see Fig. 3) is stated to be caused by the phenomenon referred to in the paper as *Inselbildung*, i.e. the non-uniformity of the electric field in the neighbourhood of the cathode surface. I should like to put forward additional reasons for this loss of mutual conductance. For purposes of calculation a triode can be replaced by an equivalent hypothetical diode whose anode voltage is

$$\frac{V_a + \mu(V_g + v)}{1 + \mu}$$

Comparing equation (5) with equation (1), it will be seen that the radius of the anode of this hypothetical diode has been assumed to be the radius of the grid (b). I question this assumption. Should not the radius be rather $a + \mu b/(1 + \mu)$, so that as $\mu \rightarrow \infty$ the radius tends to that of the grid (b), and as $\mu \rightarrow 0$ the radius tends to that of the anode (a)? Again, if the grid-voltage/anode-current curve for a triode be drawn for a given anode voltage and the origin shifted to the foot of the curve as shown at (1), Fig. A, the resulting curve will be represented by

$$i = k_s\left[\frac{\mu}{1 + \mu}V_g\right]^{\frac{3}{2}}$$

Table A

COMPARISON OF CALCULATED AND ACTUAL AMPLIFICATION FACTOR

Valve	Anode*	Grid and cathode*	s (corrected for anode ribs	ρ	P	$50\frac{s\rho}{P^2-\rho^2}$	Actual μ value
			mm.	mm.			
H30	5·5 2 ribs (2×1)	1·9 int.	2·0	0·11	0·386	80	80
PX4	5·6 4 ribs (3×1)	2·0 int.	2·0	0·15	1·66	5·5	5·5
PX25	6·0 4 ribs (3×1½)	2·0 int.	2·2	0·15	1·26	10·5	9·5
HL2	3·7 3 ribs (1×½)	0·8 int.	1·5	0·15	0·71	23·5	27
L21	3·7 3 ribs (1×½)	0·8 int.	1·5	0·15	0·82	17	16
MH4	4·4 2 ribs (1½×¾)	2·1 int.	1·2	0·15	0·525	36	40
ML4	4·4 2 ribs (1½×¾)	2·1 int.	1·2	0·15	0·825	13·5	12
A537	5·5 int. dia.	1·4 int.	2·0	0·075	0·6	21	15·5

* Dimensions in millimetres.

where the space-charge factor (k_s) is given by

$$k_s = \frac{1{\cdot}47 \times 10^{-5} l}{\left(\frac{a + \mu b}{1 + \mu}\right)\beta^2}$$

Thus it will be seen that the current i for a given value of V_g depends on the value of μ, and will be decreased in value as the number of grid turns, and hence the value of μ, is decreased, owing to both the space-charge factor k_s and the voltage factor $\left(\frac{\mu}{1 + \mu}V_g\right)^{\frac{3}{2}}$ becoming smaller. Curves (2) and (3), Fig. A, represent the resulting curves for successively larger values of grid pitch, and it will be seen that the mutual conductance for a given value of i will decrease as the pitch increases.

Equation (1) on page 402 of the paper was fairly satisfactory for most old types of valves where the radius of the anode was more than 10 times the radius of the cathode, for under these circumstances the value of β^2 is approximately unity; so that the current i for a given value of V_a is inversely proportional to the radius of the anode a and is independent of the radius or

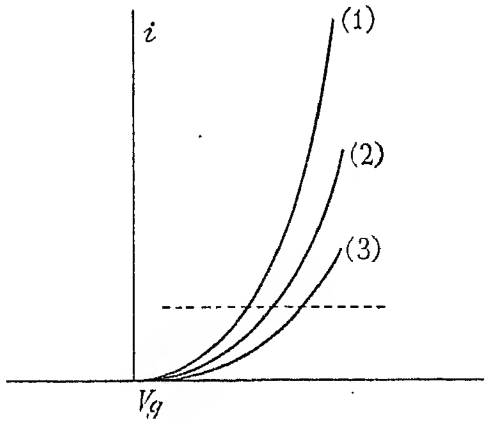


Fig. A

shape of cross-section of the cathode. This will not hold, however, for modern closely-spaced electrodes where a may be only $1\frac{1}{2}$ times c; but it will be seen from Table B that $1/(a\beta^2) \simeq a/d^2$ for all values of a/c, where d is the cathode-to-anode distance $(a - c)$, and hence instead of (1) we may write the approximate equivalent equation

$$i = \frac{Kal}{d^2} V_a^{\frac{3}{2}}$$

Thus we see that the current for a given value of V_a is proportional to the radius of the anode and inversely

Table B

a/c	$1/(a\beta^2)$	a/d^2
1·25	$18\frac{1}{c}$	$20\frac{1}{c}$
1·5	$5\cdot7\frac{1}{c}$	$6\frac{1}{c}$
2·0	$1\cdot8\frac{1}{c}$	$2\frac{1}{c}$
5	$0\cdot26\frac{1}{c}$	$0\cdot31\frac{1}{c}$
10	$0\cdot102\frac{1}{c}$	$0\cdot124\frac{1}{c}$
100	$0\cdot0094\frac{1}{c}$	$0\cdot0102\frac{1}{c}$

proportional to the square of the cathode-to-anode distance. This, of course, also applies to the triode if it is regarded as a hypothetical diode.

In connection with Fig. 12, I should like to put forward a method of considering the paths of electrons in a valve. We can represent the potential along a line in a valve by a graph such as that of Fig. 12, and similarly we can represent the potential over a cross-section by an inclined surface down which we can imagine balls, representing the electrons, as rolling. A vertical section of such a potential surface is given by Fig. 12 when turned upside down. The potential surface for a tetrode will be represented by a low ridge close to the cathode caused by the intense space charge there, this ridge having slightly higher bumps opposite the grid wires. The ball representing an electron emitted from the cathode with sufficient velocity will roll over this small ridge, otherwise it will return again to the cathode. From the top of this ridge there will be a gentle incline down to the line of the control grid. The negatively charged control-grid wires will be represented by steep hills rising to a higher level than that of the cathode. The ball will pass between these hills, probably being slightly deflected out of its original course by them. On the other side it will encounter a steep gradient down to the positively charged screen. This will accelerate the ball and straighten out its course. The screen wires will be represented by depressions; and if an electron ball is heading straight for a screen wire it will be caught, and the secondary electrons knocked off will fall again into the depression, assuming the anode to be at a lower voltage than the screen. If the ball is not going straight towards a screen wire it will be deflected out of its course by the depression in a similar manner to that of a comet passing near the sun. This deflection of the electrons is the cause of the dispersion at the screen mentioned in the paper on page 407; and will be least for small screen pitches where the depressions will be shallowest. On the opposite side of the screen the ball will encounter a rising slope up to the anode and it will have to pass over a small hump before finally reaching it. This hump is caused by the intensity of the space charge due to the slowed-up primary electrons which have become crowded together, and the proximity of secondary electrons from the anode. These secondary electrons, which are knocked off from the anode with only a fraction of the velocity of the primary electrons, are unable to climb back over the potential hump and either roll back to the anode, or, if they have been shot off obliquely, may skirt around this hump and find a straight slope down to the screen at the side, if the precautions mentioned in the paper have not been taken to prevent this.

It is stated at the top of page 423 that the use of high-frequency induction heating is to remove adsorbed gas. Surely another just as important effect is that the gas in the bulb is heated by convection currents so that its pressure is increased and the pumping speeded up.

Dr. M. Benjamin, Mr. C. W. Cosgrove, and **Mr. G. W. Warren** (*in reply*): We are in agreement with the remarks of several speakers on the desirability of standardization, limitation in the number of valve types, and reduction in the variation of characteristics. This last factor depends to a large extent on the first two, and there is no doubt that receiver designers will obtain a more uniform product when they cease to ask for higher values of mutual conductance. We cannot agree with Mr. Goldup that it is only necessary to test a very small percentage of valves for complete characteristics. While sample testing is sufficient to determine the general quality of a product and the mean value of the various characteristics, it is obviously necessary to test every valve for those characteristics to which definite limits

are set, so that any valves, however small the percentage, which fall outside those limits, shall be rejected.

The rectilinearity of the characteristics of certain triode valves to which Mr. Turner refers is largely fortuitous. A 3/2-power law characteristic approximates to a straight line over a considerable fraction of its length, and voltage saturation of the emission from the ends of the cathode makes this approximation even closer, particularly in power output valves in which the space current is an appreciable fraction of the total emission from the cathode. The production of a valve with two control grids, each of which shows a substantially constant transconductance, has been an objective of probably most manufacturers for some time, and some of the modern hexodes and heptodes do, in fact, approach this condition. The main difficulty is to maintain the transconductance at a constant value at low values of anode current where the curvature of the 3/2-power-law characteristic and the effect of the initial velocities of the electrons are greatest. We are not prepared to give an opinion on the relative merits of particular valve types in this respect.

The empirical formula for the amplification factor of a triode which Mr. Drake gives in his communication is interesting, and Table A certainly shows close agreement between calculated and measured values of μ. Referring to Fig. 3, it is true that the whole of the loss in mutual conductance in the valves which have wide grid pitches is not due to *Inselbildung*, and that from theoretical considerations we should expect the anode current and mutual conductance to depend on the amplification factor. While the formulae for anode current (i) and space-charge factor (k_s) given by Mr. Drake are more accurate than the simpler expressions given in the paper, to which in fact they approximate in practical cases for $\mu > 8$, they do not agree with the results shown in Fig. 3, and there are several additional factors, including the effect of the space charge itself on the characteristics, which should be considered. This has formed the subject of an investigation by one of us (Mr. Warren), and it is hoped to publish the results in the near future. Referring to the measurement of the conversion conductance of frequency-changers, it is not implied in the paper, as Mr. Harvey suggests, that the high-frequency method is less accurate than the low-frequency method. The statement made on page 430 is " This method, though more rapid than the low-frequency test, suffers from the disadvantage that it is not absolute and frequent calibration is necessary." The subject has been discussed in more detail in a paper by Stewart.*

We cannot agree with Mr. Gill's statement that a greater life for the ordinary wireless valve " is a matter of greatly increasing importance at the present time." While it is true that the emission life of valves may vary between 100 and 4 000 hours (much greater lives are frequently obtained) the actual percentage of modern valves in common use which have lives of less than 500 hours is negligible. The argument that if a receiver has 30 valves in it and that if each lasts 100 hours, over 2 000 valves will need replacing in that receiver every year, is meaningless, since the probability of such an event is of the order 10^{-3000}. We imagine that the actual valve-replacement cost met in practice would show the average life of a receiving valve to be very much greater than 1 000 hours, and most valves do, in fact, outlive the receivers in which they are put.

We have not encountered the difficulties which Mr. Goodchild suggests might be expected with the bead form of heater insulator, although we agree that this method of preventing broken filaments is not ideal. Where a hairpin filament is used, however, our experience has shown that the use of a coating material which has been pre-shrunk to a maximum density leads to a far greater percentage of filament failures than the bead form of coating, since in the latter case the heater and coating are free to expand and contract independently. Vibration tests are undoubtedly desirable and it has been the practice, in the organization which we represent, to life-test some valves under vibration conditions. We appreciate the essential difference between the a.c. and the d.c. method of measuring leakage referred to by Dr. Sturley, but our experience has been that the results of the two methods can be correlated, and the d.c. test is more convenient. We have not observed the tendency for leakage currents to reappear after the conduction of the coating has been poisoned in the way described, and we suggest that where this does occur the " leakage " may be thermionic emission between the heater and cathode.

Several of the questions refer to secondary emission. By secondary-emission coefficient is meant the ratio of the number of secondary electrons emitted to the number of primary electrons striking the electrode. A satisfactory account of the effect of the angle of incidence of the primary electrons has been given only since the present paper was written. Bruining† has shown that, in general, the secondary-emission coefficient increases with the obliquity of the primary electrons. Mr. Moullin's remarks on the initial velocities of secondary electrons are correct. By " low initial velocities " we meant velocities which are small, though not negligible, compared with the velocity acquired by an electron in falling through a potential difference normally existing between the screen-grid and cathode. The secondary electrons have, however, a wide energy distribution ranging from zero to the energy of the primary electrons. Thus Haworth has shown‡ that, for molybdenum bombarded with 150-volt electrons, though the most probable energy of the secondaries is about 3 volts, about 50 per cent have energies greater than 10 volts, and 16 per cent have energies greater than 30 volts. These figures are not directly applicable to the problem of determining the secondary-electron current in a valve when the potential distribution is given. For example, in a system of plane parallel electrodes, it is the normal component of energy which determines whether an electron from the anode will reach the screen, and the normal components of energy are necessarily considerably lower than the total energies.§

Mr. Walker's view that a good deal of noise in valves is due to secondary emission from mica insulators is interesting, and there is no doubt that the insulators can emit secondary electrons. As explained in the paper, a given point in the insulator can assume either zero

* *Journal I.E.E.*, 1935, vol. 76, p. 227.

† *Physica*, 1936, vol. 3, p. 1046.
‡ *Physical Review*, 1935, vol. 48, p. 88.
§ L. R. G. Treloar: *Nature*, 1936, vol. 137, p. 579.

or some high positive potential depending on the secondary-emission properties and insulation resistance of the insulator and the space charge in the neighbourhood of the point. There must, therefore, be some discontinuity or very steep potential gradient on the surface of the insulator somewhere between the control-grid and anode supports. If the position of this discontinuity moves, one will expect noise. It is, however, difficult to decide whether this factor or variable leakage is mainly responsible for noise. In the first place, the secondary currents depend to some extent on the leakage, and secondly, in a valve with metal shields such as Mr. Walker suggests, these shields, while preventing secondary emission, will also prevent the deposition on the insulator of barium from the cathode, and thus reduce the surface leakage.

We agree with Dr. Sturley that the impedance of the majority of coils used in broadcast receivers may be only 0·1 to 0·15 megohm, but the valve maker must remember that any one of his valves may be required to operate with circuits which do exist having impedances of up to 0·5 megohm. The valves must therefore be designed on the basis of this higher figure.

Several speakers refer to the acorn valve, and Dr. Smith-Rose mentions the demand for valves with a good performance at wavelengths between 2 and 10 metres. This problem is receiving considerable attention, and the acorn valve, which is now being produced in this country, may not necessarily be the best solution.

The difficulties inherent in the design of an indirectly-heated output triode are mentioned in the paper. There is no doubt that a demand exists for such a valve, and improvements in manufacturing technique have increased the possibility of making such a valve. The feed-back principle applied to output stages does, of course, remove some of the disadvantages of the pentode.

The ring seal has recently been used more and more in transmitting valves, particularly those designed for short waves, but up to the present its adoption in receiving valves has been limited on account of the changes in manufacturing technique involved and the capping difficulties, and also because with the modern practice of bringing the grid lead to the top of the valve the standard form of pinch is satisfactory.

The metal valve recently produced in America differs in many essential features from the valves introduced in this country a few years ago under the registered trademark "Catkin." In the latter the anode formed part of the envelope, whereas the American metal valve is simply a standard electrode system in a metal envelope. It does not appear that the manufacture of metal valves, particularly of the air-cooled anode type, can be carried out as economically as that of glass valves, while new types are continually being introduced, owing to the less flexible nature of the plant required for metal valves.

We did not refer in great detail to the vapour process, since this method of producing a dull-emitting cathode is almost obsolete, and is not likely to be revived. The "beam valve" was not referred to as such, although the principle was mentioned in Fig. 9. The additional feature of the beam valve, namely the aligned grids, is not novel, but manufacturing difficulties had prevented the adoption of this feature until recently. Other omissions from the paper were due to our desire to keep it within a reasonable length.

Several speakers refer in the early part of the discussion to the importation of foreign words into the English language. We do not think it desirable to lay down any hard-and-fast principles on this subject. The words *Durchgriff* and *Ruckgriff*, for example, express particular electrical properties of systems of electrodes for which there are no convenient expressions in English. Other words, such as *Inselbildung*, have been adopted as the result of common usage amongst valve engineers. The international nature of science is likely, we suspect, to increase rather than decrease the number of such words. Dr. Bartlett refers to the use of the expression "contaminated-metal emitters"; this is perhaps an unfortunate expression, and might be misleading if taken out of its context. "Foreign-layer emitters" is perhaps a more suitable alternative, but it is, we think, too late to suggest this change since "contaminated-metal emitters" has already been generally accepted, and appears in Reimann's book.* We have resisted the temptation to suggest *schichtkathoden !*

We wish to thank Mr. Goldup for pointing out the error in the values given in the advance copies for the anode-grid capacitance of screen-grid valves. This has been corrected for the *Journal*.

In regard to Dr. Bartlett's comments on the use of phosphorus as a getter, this getter was used in many bright-emitter valves, but he is correct when he says that it was the use of magnesium as a getter which made the thoriated tungsten filament a real commercial success. We also wish to thank Mr. Goodchild for pointing out that the oxide-coated cathode was used commercially as early as 1914. We believe, however, that the first published work on the subject appeared in 1920.†

We are in agreement with Mr. Walker's criticism of some of the symbols used in the advance copies of the paper, and have taken the opportunity of altering these throughout to conform with those in the British Standard Glossary.‡

* "Thermionic Emission" (Chapman and Hall, 1934).
† H. D. ARNOLD: *Physical Review*, 1920, vol. 16, p. 70.
‡ B.S.S. No. 205, Nov., 1936, p. 249.

MEASUREMENTS OF THE HIGH-FREQUENCY RESISTANCE OF SINGLE-LAYER SOLENOIDS*

By WILLIS JACKSON, D.Sc., D.Phil., Associate Member.

(*Paper first received* 11*th June and in final form* 27*th November*, 1936.)

SUMMARY

The paper describes an attempt to determine experimentally the accuracy of Butterworth's formulae for the high-frequency resistance of single-layer solenoids. The investigation has been carried out on 4-in. diameter air-spaced coils of 10, 30, and 50 turns over the frequency range from 2×10^5 to $2 \cdot 025 \times 10^6$ cycles per sec. The coils were wound with bare wire of diameter $1 \cdot 63$ mm. (No. 16 S.W.G.), with a distance of $2 \cdot 60$ mm. between the centres of adjacent wires. The method of measurement described was based on the use, for each coil shape, of a series of identical coils wound with copper, aluminium, brass, german silver, and eureka wire, respectively. There is some uncertainty in the interpretation of the results, but, in spite of this, it is evident that of the two formulae with which a comparison is made, one of them is correct to within about 4 per cent for the 30- and 50-turn coils over the whole frequency range considered. This formula is quite inapplicable to the 10-turn coils; however, for these the second formula gives reasonably good agreement with the experimental results.

INTRODUCTION

In 1921, S. Butterworth published a classic paper† on the high-frequency resistance of short single-layer coils; this was followed by two other papers‡ which extended the original work to coils of any length and any number of turns. His formulae have not been subjected to searching experimental tests, however, because there are certain outstanding difficulties in doing so. The precision uses of bridge networks are not available at radio frequencies, and at such frequencies it is usually possible to measure directly only the total resistance of a circuit containing a tuning condenser also. Since this resistance value will include the effect of energy-loss in the condenser and in the supports with which the coil is normally provided, it is commonly much in excess of the calculated resistance of the coil alone. The condenser loss cannot in general be measured separately, and hence it has not been possible to tell whether the coil resistance agrees with the value calculated by Butterworth's formulae.

In 1928, D. W. Dye§ developed an elegant method of measuring the energy loss in a specially constructed condenser. A condenser calibrated by his method could be used in a circuit constructed to test Butterworth's formulae, provided always that the loss in the coil supports could be ignored, and that due to the indicating instrument allowed for. Dye's method does not, however, appear to have been developed further. In 1931, E. B. Moullin† developed a very simple method of measuring simultaneously both the coil resistance and the condenser loss, subject of course to the above proviso. The method consists in providing a series of coils which are identical in all respects save the metal used for the wire. The total circuit resistance is measured with identical coils of copper, aluminium, brass, etc., and when this measured resistance is plotted against the calculated value, a straight line, which does not pass through the origin, should result. The intercept on the axis of measured resistance gives the value of a residue, which is independent of the resistance of the coil and is therefore attributable to the condenser, the coil support, and the indicating instrument. The slope of the line is a measure of the agreement between the calculated and observed resistance of the coil. It should be noted that similar coils have the same inductance and hence the appropriate capacitance is independent of the wire material. This method was developed for the purpose of studying condenser loss. The paper referred to was concerned mainly with studying the validity of the method, and incidentally checked the well-known formula for the high-frequency resistance of a long straight wire. In 1934, the author‡ made use of it in a study of the loss components in a certain air condenser. It seemed possible that the method would provide a means of checking experimentally Butterworth's formulae, and a description of the resistance measurements which have been made, and their comparison with Butterworth's values, is given below.

OUTLINE OF BUTTERWORTH'S WORK

In his first paper§ Butterworth calculated the high-frequency resistance of a band of similar parallel wires, each of diameter d and with their axes separated by a distance D. He showed that the effective resistance of a wire depended on its position in the band but that its average resistance R_f at frequency f was related to R_0, the direct-current resistance per unit length, by the equation

$$\frac{R_f}{R_0} = \left[1 + F(z) + u_n \frac{d^2}{D^2} G(z)\right] \quad . \quad . \quad (1)$$

where u_n is a factor depending on the number of wires in the band and $F(z)$ and $G(z)$ are certain functions of a parameter z defined by the relation

$$z^2 = \frac{2\pi^2 f \mu d^2}{\rho} = \frac{8\pi f \mu}{R_0} \quad . \quad . \quad . \quad . \quad (2)$$

He tabulates values of $F(z)$ and $G(z)$ and shows that, when $z > 5$, $F(z) \simeq (z\sqrt{2} - 3)/4$ and $G(z) \simeq (z\sqrt{2} - 1)/8$,

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† See Reference (1). ‡ *Ibid.*, (2), (3). § *Ibid.*, (4).

† See Reference (5). ‡ *Ibid.*, (6). § *Ibid.*, (1).

u_n ranges from 1 to $\pi^2/3(=3\cdot29)$ as the number of wires increases from 1 to ∞; for 32 wires, $u_n = 3\cdot00$. The derivation of equation (1) contains the approximation that the magnetic field is uniform over the cross-section of any individual wire; consequently it must not be applied when d/D is near unity.

He then considers the effect of bending the flat band of wires into a coil, and shows that equation (1) can be retained, provided that u_n is now replaced by a different factor u_c, given by

$$u_c \simeq 3\cdot29 + \frac{b}{a} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

for coils of length b and radius a and where $b < 2a$. The value of the constant term in (3) suggests that the coil is supposed to have many turns, say not less than 40.

In the 1925 paper* Butterworth made a notable extension of equation (1), as modified by (3), in the form of the following equation (4):—

$$\frac{R_f}{R_0} = \left\{\alpha\left[1 + F(z)\right] + G(z)\left[\beta u_1 + \gamma u_2\right]\frac{d^2}{D^2}\right\} \quad . \quad (4)$$

in which there is no restriction either on the value of d/D or on that of $b/(2a)$. α, β, and γ are tabulated functions of d/D and z, and u_1 and u_2 tabulated functions of the length-to-diameter ratio of the coil. Equation (4) is not general, however, because it is derived for a coil having " an extremely large number of turns."

Section (10) of this 1925 paper deals with the resistance of coils having a finite number of turns, but these are to be very short: for such coils he finds that

$$\frac{R_f}{R_0} = \left[1 + F(z)\left(1 + \frac{1}{8}w_n\frac{d^4}{D^4}\right) + u_n G(z)\frac{d^2}{D^2}\left(1 + \frac{1}{2}v_n\phi_1\frac{d^2}{D^2}\right)\right] \quad (5)$$

in which u_n, v_n, and w_n are tabulated as functions of the number of turns, and ϕ_1 as a function of z.

The coil of any length and a finite number of turns has not been dealt with. This is unfortunate, because the single-layer solenoids employed in radio-frequency practice are not commonly very short and yet have no more than, say, 50 turns. Hence there is as yet no exact formula for the resistance of many single-layer coils of wide radio-frequency application.

In the subsequent analysis the discussion of the experimental results has been limited to a comparison with the above equations (4) and (5) as given by Butterworth in his final paper.† For the coils on which measurements have been made, these formulae give appreciably different resistance values. The figures given in Table 1 were obtained on applying (4) and (5) at a frequency of 1 149 kc (261·1 metres) to a group of similar 10-turn coils to be described later ($d/D = 0\cdot626$ and $b/a = 0\cdot46$), at a temperature of 18° C.

It is seen that, for these particular coils, equation (4) predicts resistances which are from 47 to 20 per cent greater than those provided by equation (5), over the range of z from 18·70 to 3·38.

The results of a similar comparison for a group of 30-turn coils ($d/D = 0\cdot626$ and $b/a = 1\cdot48$) are given for the same frequency, 1 149 kc, in Table 2.

The discrepancy is not so marked with these coils; it varies from 23 to 12 per cent over the relevant range of z.

There seems no obvious way of modifying equation (4) to allow for a finite number of turns, but it would seem reasonable to modify (1) by using in (3) the value for the constant term appropriate to a flat band having the same number of wires as the coil. Thus for the 30-turn coils this becomes 3·00 *vice* 3·29. Equations (1) and (3) as they stand give values of R_f/R_0, corresponding to the z values of Table 2, of 13·00, 9·75, 6·29, 3·05, and 2·32 respectively; the modified figures are 12·50, 9·38, 6·07, 2·99, and 2·28. The effect is only of the order of 3 per cent, and perhaps there is thus reason to hope that equation (4) should predict the resistance of the 30-turn coils concerned to this degree of accuracy.

Table 1

Type of conductor		Copper	Aluminium	Brass	German silver	Eureka
$z =$		18·70	14·08	9·14	4·43	3·38
R_f/R_0	by eqn. (4)	16·96	12·52	7·79	3·39	2·45
	by eqn. (5)	11·49	8·64	5·57	2·71	2·05

Table 2

Type of conductor		Copper	Aluminium	Brass	German silver	Eureka
$z =$		18·70	14·08	9·14	4·43	3·38
R_f/R_0	by eqn. (4)	16·16	11·98	7·54	3·37	2·48
	by eqn. (5)	13·06	9·75	6·25	2·97	2·22

DESCRIPTION OF THE COILS USED IN THE MEASUREMENTS

The coils were wound with wire of 1·63 mm. diameter (No. 16 S.W.G.) with a distance between wire centres of 2·60 mm. The wires used were copper, aluminium, brass, german silver, and eureka alloy. There were three sets of similar coils having 10, 30, and 50 turns, all of 10·2 cm. mean diameter and of axial lengths 2·34, 7·57, and 12·75 cm. respectively. All the coils were self-supporting, without any former, by means of their own stiffness assisted by six waxed-cotton lashings threaded axially along the coil. This method of construction was devised some years ago by the author and has been described previously.*

The direct-current resistance at 18° C. ranged from 0·0275 ohm for the 10-turn copper coil to 3·85 ohms for the 50-turn eureka coil. The values of R_0 used in the derivation of the high-frequency resistance R_0 were corrected for the room temperature obtaining at the time of a particular measurement. The inductance of the

* See Reference (3). † *Ibid.*, (3).

* See Reference (7).

similar coils of each group was the same to within less than $1 \cdot 0$ per cent; the values for the 10-, 30- and 50-turn groups were $14 \cdot 9$, $66 \cdot 6$, and $145 \cdot 2\ \mu$H, respectively. Measurements were made at eight frequencies within the spectrum of broadcasting stations, and for these the

Table 3

VALUES OF z

Frequency	Copper	Aluminium	Brass	German silver	Eureka
kc					
200	7·79	5·88	3·81	1·84	1·41
271	9·09	6·86	4·45	2·05	1·64
546	12·84	9·70	6·30	3·05	2·33
668	14·24	10·76	6·99	3·38	2·59
877	16·30	12·30	7·99	3·87	2·95
1 149	18·70	14·08	9·14	4·49	3·38
1 474	21·15	15·97	10·32	5·01	3·82
2 025	24·90	18·70	12·10	5·89	4·48

relevant values of z are shown in Table 3. It will be seen that the frequencies and materials chosen cover a range of z from $24 \cdot 90$ to $1 \cdot 41$.

EXPERIMENTAL PROCEDURE

The coils formed in turn the inductive part of a simple resonant circuit, and their resistance was deduced by measuring the fractional width of the resonance curve. The capacitances employed were high-quality variable air-condensers for laboratory use, and call for no special comment. The indicating instrument was a valve voltmeter connected across a small portion of the coil. The resonance curve may be delineated either by incremental adjustment of the oscillator frequency about the resonant value, or by vernier condenser variation on the test circuit. The frequency-variation method was adopted, but the capacitance-variation one was used occasionally to provide a check on the accuracy of the measurements. The fractional width at $1/\sqrt{2}$ of the height gives the circuit power factor, $R/(2\pi fL)$, and if the frequency and inductance are known, R, the circuit resistance, can be calculated. The frequencies were chosen to coincide with those of certain broadcasting stations, since these frequencies are maintained constant at their declared values to a high degree of accuracy. Calibration of the local radio-frequency oscillator for incremental frequency-changes was performed by "double beating" it with the appropriate broadcasting station and a calibrated audio-frequency source. The absolute value of the audio frequency was known to within 1 per cent. To reduce the duration of individual measurements, and thus to avoid possible error due to a slight tendency to frequency-drift in the local oscillator, it was not usual to plot the whole resonance curve, but merely to record the change in reading of the fine-adjustment condenser required to bring the voltmeter reading rapidly from $1/\sqrt{2}$ of the resonant value, up through this maximum, and down to $1/\sqrt{2}$ on the far side of the curve. This procedure was repeated four or five times for each measurement and the mean value used in the power-factor derivation. In general, the departures from the mean were not more than $0 \cdot 25$ per cent. A thermal ammeter was included in the oscillator in order to show that there was never any change of output as the frequency was varied over the desired range about the resonant value. The agreement between comparative results on individual coils obtained by the frequency-variation and circuit-capacitance-variation methods was usually within 2 per cent.

The accuracy of the subsequently deduced agreement between the measured and calculated coil-resistance values involves the possibility of (*a*) accidental errors in measuring the circuit resistance for any one of a group of coils, (*b*) a systematic error running through a group as a whole, and (*c*) the possibility that the plot of the measured circuit resistance and calculated coil resistance may not naturally form a perfect straight line. The deviation of individual points from the mean-square straight lines whose slope has been used to derive the desired agreement figures plotted in Figs. 1, 2, and 4, was, however, seldom outside the limits of ± 2 per cent. It seems probable that this is the order of the overall accuracy of the measurements.

DISCUSSION OF EXPERIMENTAL RESULTS

The basis of the analysis consists in obtaining the slope of the line representing the presumed linear relation between the measured circuit resistance and the calculated coil resistance. In each set of observations this relation has been obtained from a mean-square solution, and the derived slope has been taken as a measure of the correctness of Butterworth's formulae.

10-Turn Coils

Fig. 1 shows the percentage deviation of this slope from unity, plotted on a log (frequency) basis, for the 10-turn coils, the comparison being with the "short coil" equation (5). This equation apparently underestimates the coil resistance by about 5 to 10 per cent.

Equation (4), on the other hand, cannot be expected to be applicable to these coils, and indeed the resistance values calculated from it provided points which did not

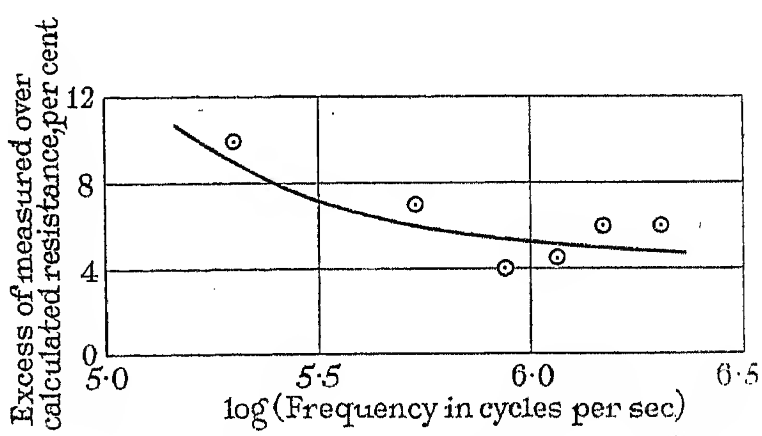


Fig. 1.—Results obtained with 10-turn coils: comparison with equation (5).

lie at all satisfactorily on straight lines. These calculated values were in general greater even than the measured total circuit resistance, including the condenser and voltmeter loss. The latter may be allowed for by making use of the circuit residual deduced from the application of equation (5), and when this was done the excess of the

calculated—equation (4)—over the measured coil resistances was particularly marked. The results for the 10-turn copper coil are tabulated in Table 4, from which it appears that equation (4) over-estimates the coil resistance by as much as 40 per cent at the higher frequencies. This is consistent with the comparison between equations (4) and (5) in Table 1 where, for the copper coil at 1 149 kc, the former equation gives a resistance value 50 per cent greater than equation (5).

Table 4

10-TURN COPPER COIL: COMPARISON WITH EQUATION (4)

Frequency	Measured circuit resistance	Circuit residual, deduced from application of eqn. (5)	Estimated coil resistance	Calculated coil resistance, from eqn. (4)	Excess of calculated over estimated resistance
kc	ohms		ohms	ohms	per cent
200	0·172	0·024	0·148	0·175	18·0
546	0·287	0·040	0·243	0·305	25·0
866	0·386	0·095	0·290	0·405	40·0
1 149	0·445	0·120	0·325	0·465	43·0
1 474	0·580	0·200	0·380	0·530	40·0
2 025	0·670	0·220	0·450	0·630	40·0

30-Turn Coils

The more appropriate equation for this group of coils is clearly (4); since the ratio of length to radius (b/a) was 1·48, the 30-turn coils cannot be described as very short and, following Butterworth, equation (5) is certainly not applicable. This decision is supported by the curves of Fig. 2, which show the percentage discrepancy between the measured and the respective calculated resistance values for frequencies extending from 2×10^5 to

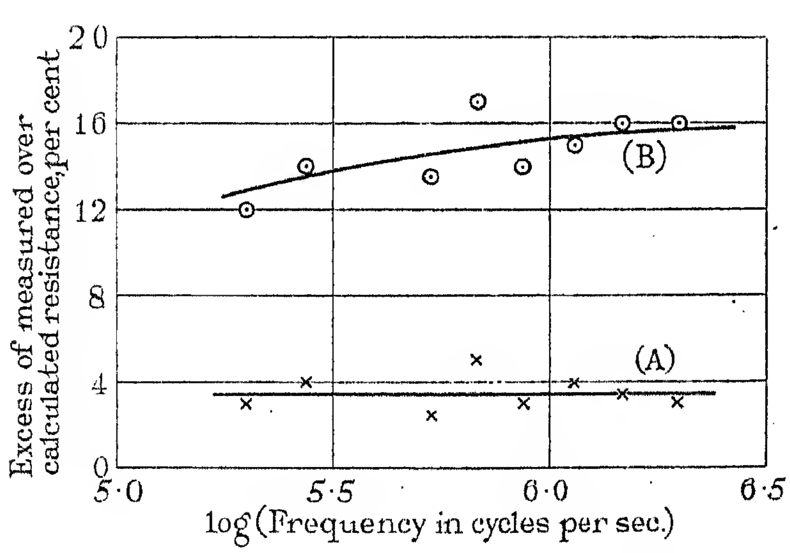


Fig. 2.—Results obtained with 30-turn coils.

(A) Comparison with equation (4).
(B) Comparison with equation (5).

$2{\cdot}025 \times 10^6$ cycles per sec. It appears that both (4) and (5) under-estimate the resistance of this group of coils, but that now, contrary to the 10-turn coil behaviour, equation (4) gives much the closer agreement—4 per cent as against about 15 per cent—with the measured values.

The discrepancy values plotted in Fig. 2 are not really so convincing, however, as they may appear to be. To demonstrate this, the plot of a typical set of individual results—those obtained at 1 149 kc (see Table 2)—is shown in Fig. 3. The slopes of the two lines, (A) and (B), connecting the measured circuit resistance and the coil resistance calculated from equations (4) and (5) respectively, are 1·04 and 1·15. From this it is inferred that at 1 149 kc equation (4) under-estimates the coil resistance by 4 per cent, and equation (5) does so by 15 per cent. The logical deduction from a statement of these as the respective agreement figures would be that for each coil of the 30-turn group there is a discrepancy between the two formulae of about 11 per cent. Actually, however, as shown in Table 2, the discrepancy between

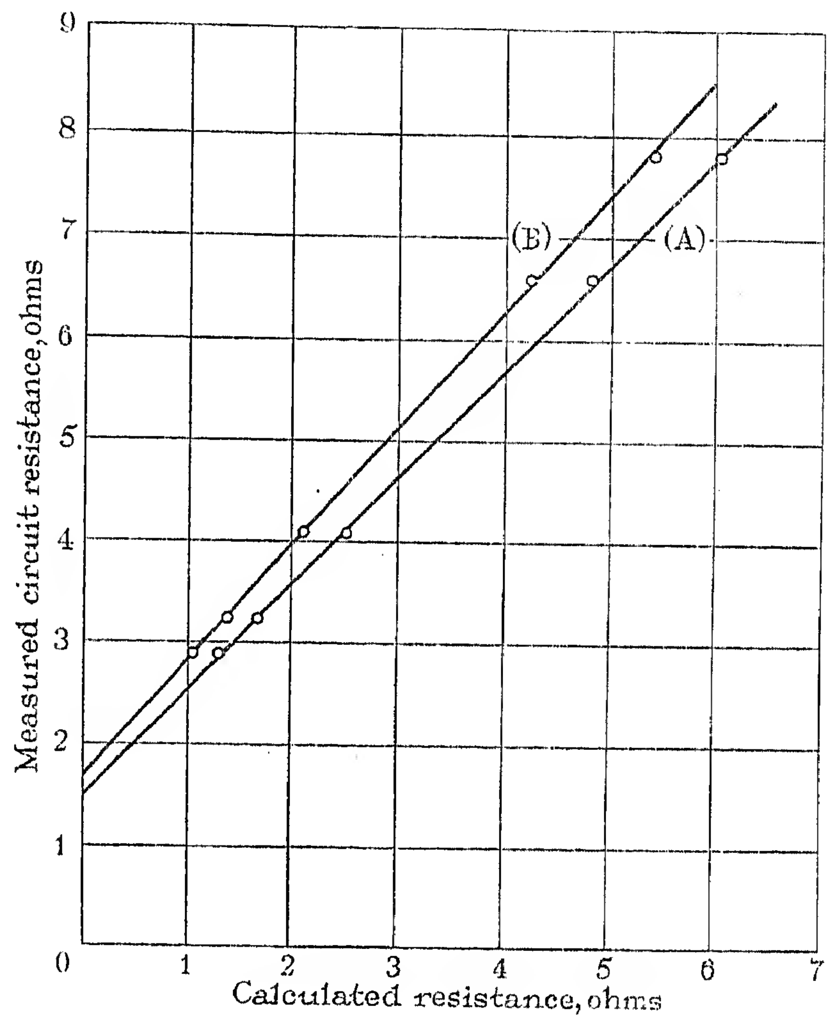


Fig. 3

(A) Coil-resistance values for 30-turn coils calculated from equation (4).
(B) Coil-resistance values calculated from equation (5).

the two formulae varies from coil to coil owing to the widely different values of z occasioned by the different specific resistances of the several wire materials. Taken relative to equation (4) the percentage discrepancies are 24, 23, 21, 13·5, and 11·5 for the copper, aluminium, brass, german silver, and eureka coils; or relative to equation (5) they are 19, 18·5, 17, 12, and 10·5, respectively. The discrepancy experiences variations over the group of coils which are of the same order of magnitude as the inferred disagreement with Butterworth's formulae at this frequency.

The discrepancy values given in Fig. 2, and also of course those in Fig. 1, have really been deduced on the supposition that the intercept on the measured-resistance

axis of curves typified by Fig. 3 is indeed the residual circuit resistance not associated with the coil. The evidence for this supposition has been the linearity of the latter curves. It now appears, however, that this evidence is insufficient. Thus the points in Fig. 3 provided by the inapplicable "short coil" equation (5) lie on a straight line quite as satisfactorily as those given by the more appropriate equation (4). Presumably a part of the difference between the respective calculated resistances is a constant which affects only the apparent circuit residual, while another part is a proportionate quantity which reveals itself in the difference in slope of the two lines. One is left somewhat doubtful, therefore, as to the real significance of this difference in slope and consequently of the individual slopes. Thus, as an extreme case, suppose that the two formulae had given values for the resistance of the several coils which differed only by a constant amount; a plot similar to that of Fig. 3 would give two lines of identical slope, indicating an (impossible) identical agreement with the measured-resistance values in both cases. No distinction would then be possible in the absence of a decision as to which of the two indicated circuit residuals was the correct

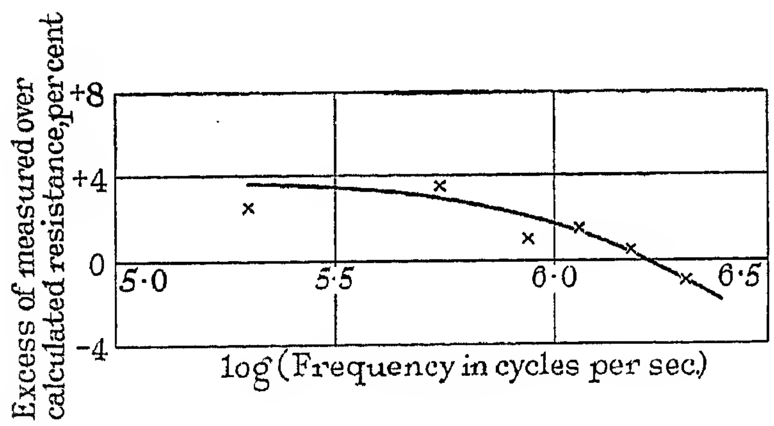


Fig. 4.—Results obtained with 50-turn coils: comparison with equation (4).

one. This, however, introduces the fundamental difficulty which it was hoped to avoid by the application of the method.

The uncertainty referred to above is not sufficiently marked, however, for there to be any doubt that equation (4) is distinctly superior to equation (5) for application to the 30-turn coils, and that for these it gives resistance values which are very closely correct.

It is important to note that the residual circuit resistance of 1·52 ohms given by curve (A) of Fig. 3 corresponds to an equivalent condenser power factor, including the effect of voltmeter damping, of $3 \cdot 1 \times 10^{-3}$. This is a very reasonable figure for the type of variable condenser employed.

50-Turn Coils

Equation (5) is clearly inapplicable to this group of coils, and a comparison of the experimental results has been made only with equation (4). The percentage discrepancy between the measured resistances and those calculated from the latter equation is shown in Fig. 4. As might be expected, the agreement is even better than in the case of the 30-turn coils, being within 3 per cent over the whole frequency range from 200 to 2 025 kc. It appears, therefore, that equation (4) can be used with confidence for the calculation of coils of the type described, possessing a number of turns in excess of about 30.

EFFECT OF NON-UNIFORM CURRENT DISTRIBUTION DUE TO COIL SELF-CAPACITANCE

Since the circuit resistance has been derived from voltage measurement on the coil,* and from a knowledge of the true inductance L through the relation $R/(2\pi fL)$ for the measured power factor, the self-capacitance of the coil has not entered into consideration as a significant quantity. Where the frequency of measurement approaches the natural frequency of the coil, however, it is to be expected that the self-capacitance will influence the effective coil-resistance through the production of a non-uniform distribution of current along the length of the coil.†

In order to determine the importance of this effect, the circuit arrangement was modified in such a way that following a measurement with the coil supported in air, it could, without disturbance, be immersed completely in a liquid of high dielectric constant. The measurement was then repeated at the same frequency, the increase in coil self-capacitance being compensated by a corresponding decrease in the external tuning capacitance. This procedure was carried out for a group of five similar coils, and the slope of the line connecting the measured circuit resistance and the calculated coil resistance determined as before.

It is sufficient to record the results on the 50-turn coils at a frequency of 1 474 kc. When completely immersed in butyl phthalate (dielectric constant 6·72), the natural frequency of the isolated coil was found to be 3 030 kc. This corresponds to an effective self-capacitance of 19·0 $\mu\mu$F, and a self-capacitance in air of 2·8 $\mu\mu$F. The measuring frequency of 1 474 kc was therefore about one-half the natural frequency of the immersed coils, and considerable non-uniformity of current distribution is to be expected. The immersion produced no appreciable change, however, in the slope of the line connecting the measured circuit resistance and the coil resistance calculated from equation (4), although it caused a marked increase in the residual resistance, due presumably to dielectric loss in the liquid surrounding the coil. Before immersion the agreement given with equation (4) was within 1 per cent, and after immersion 2·5 per cent. The difference between these two figures is inside the limits of experimental error, and it would seem, therefore, that the non-uniformity of current distribution arising from self-capacitance does not normally influence the coil resistance.

Acknowledgment is due to the Advisory Council of the Department of Scientific and Industrial Research for a grant which made this investigation possible, and to Mr. E. B. Moullin, M.A., for his interest during the carrying out of the work in the Engineering Laboratory, Oxford.

* The effect of self-capacitance on the apparent coil resistance when current measurement is employed, is dealt with by Moullin [see p. 346 of Reference (8)].
† See p. 356 of Reference (8).

REFERENCES

(1) S. BUTTERWORTH: *Philosophical Transactions of the Royal Society*, 1921, vol. 222, p. 57.
(2) S. BUTTERWORTH: *Physical Review*, 1924, vol. 23, p. 752.
(3) S. BUTTERWORTH: *Proceedings of the Royal Society*, A, 1925, vol. 107, p. 693.
(4) D. W. DYE: *Proceedings of the Physical Society*, 1928, vol. 40, p. 285.
(5) E. B. MOULLIN: *Proceedings of the Royal Society*, A, 1932, vol. 137, p. 116.
(6) W. JACKSON: *Proceedings of the Institute of Radio Engineers*, 1934, vol. 22, p. 957.
(7) W. JACKSON: *Wireless Engineer*, 1928, vol. 5, p. 255.
(8) E. B. MOULLIN: " The Theory and Practice of Radio-Frequency Measurements," 2nd edn. (Griffin and Co.).

DISCUSSION ON "CINERADIOGRAPHY"*

NORTH MIDLAND CENTRE, AT LEEDS, 24TH NOVEMBER, 1936

Dr. L. A. Rowden: The author's apparatus requires a current of about 60 mA at 100 kV, corresponding to 30 amperes in the 200-volt primary, but the amount of energy absorbed on the cinematograph film is extremely small.

The power-supply frequency of 50 is not very suitable for the author's purpose, and in some of the work for which the apparatus is used greater adjustment of the exposure is desirable.

Turning to the question of fluorescent screens, if one could get a fluorescent substance which would give the infra-red type of radiation it might be of considerable advantage.

I should like to know the cost of this type of apparatus and whether cineradiography is expensive. Lord Nuffield has, I believe, recently given a large sum of money for this work at the University of Oxford.

Dr. J. M. Lees: The author's apparatus provides economy of time, space, and money, particularly for demonstration purposes and for students. Take, for example, the process of swallowing, which the author's demonstration showed. I attempted at one time to reproduce this with a film for a physiological class by allowing a coloured bolus to fall down the throat of a black-and-white outline, in a way similar to that in which a " Micky Mouse " picture is made. The maximum number of frames that one could take was about 400 in an hour, and after taking this number one felt quite exhausted.

We once made a film of the movements of the foot as shown by Mr. Lambrinudi, the orthopaedic surgeon; this was only run for about 10 minutes, and one can quite appreciate that any " cutting " meant a sacrifice of many hours' work. The author, on the other hand, can gather all the circumstances on a film with his apparatus in the course of a few minutes and run it for as long as he likes, and any cutting may merely mean financial hardship.

As regards the question of space, I may remark that I have spent some time with Dr. Robert Janker of Bonn, who, instead of the small compact apparatus employed by the author, used a small lead-lined box the size of an " Austin 7 " saloon car, in which he fitted himself, his secretary, his head mechanic, and any visitors that happened to be present. The majority of his work has been done upon animals, which, from the operator's point of view, have the advantage of being thin and easily irradiated.

Abroad there is a tendency to fake many cineradiographic results, by adopting the cartoon method of doubling up the frames. I should like to know how many pictures a second the author is taking, for he is obviously showing more than 16 a second in order to give the appearance of continuity.

Dr. Rowden has already touched upon the question of cost. I should like to know whether the apparatus will come within the purchasing range of such persons as myself, or whether it is still an expensive toy reserved for academic bodies.

Mr. F. Gurney: I believe the discovery of X-rays was accidental. It arose as the result of some photographic plates being affected by these rays while experiments were being carried out near the plates, which were still in their ordinary wrappings. That means that X-rays themselves affect the photographic plate. The lens of the camera, however, can only deal with light waves. What I cannot understand is how a change of wavelength from X-rays to light rays is effected on the fluorescent screen. Also, what sort of light is employed in the dark-room when films are being changed?

A lot of difficulties seem to have arisen in regard to synchronizing the shutter, so that the shutter is open when the emanations are at their peak value. As the emanations are derived from an alternating-current source, it occurs to me to ask whether any stroboscopic methods have been tried to ensure synchronism between X-ray emanations and shutter position and speed.

Dr. Rowden referred to difficulties arising from the fact that a frequency of 50 cycles per sec. is now almost universally available. I would suggest that any such difficulties might be overcome by providing suitable frequency-changers.

Mr. W. S. Stuart: On page 396 (vol. 79) there is a reference to the cover of the camera incorporating a

* Paper by Dr. R. J. REYNOLDS (see vol. 79, p. 389).

source of red radiation, presumably to deal with the afterglow of the screen. I should be glad if the author could give some further details of that feature.

Mr. J. G. Craven: Hitherto I had always understood that the heart was to the left of the human frame. In the author's films of the heart's action, however, the heart appeared to be central in the body. I should like confirmation that this is actually the case.

Prof. A. Hemingway: In late years tremendous interest has been taken in the anatomy of the living as opposed to anatomy studied in the dissecting room. X-ray examination has been a valuable method in such studies and in the solution of many of our problems in physiology. It can be realized how difficult it has been in the past, however, to demonstrate details on a dimly illuminated screen to a class of 50 students. Cineradiography offers a method whereby details which could hardly be observed on the ordinary screen by an individual can now be demonstrated to a class of practically any dimensions. The pictures of the beating heart seen in the author's demonstration were far clearer than one could hope to show by any other means. Another advantage is that the film can be stopped at any moment, so that any particular point can be demonstrated to further advantage. When the author has succeeded in speeding up still more his rate of taking, then slow-motion pictures of the human heart will make possible still closer analysis. From studies such as these we can anticipate great progress in our study of both the normal and the diseased heart.

The development of cineradiography illustrates a point which, I suppose, is common to many technical advances. For although, when the author started his work, the principles on which he would have to build were fairly well understood, yet he has been many years on the perfection of details necessary to the production of such films as he is now able to show.

Before a university department can consider the application of new methods in its teaching it must concern itself with their cost. In general, universities are not able to face large expenses, but one solution which might be applicable to this type of work is that research institutes such as that of the author, or the new cinema institute which is being developed in Oxford, should provide the provincial schools with a sufficient supply of films. Whether such a scheme would also be sufficient to meet the needs of those who require cineradiography for diagnostic purposes it is hard to say. It might be possible to establish centres in various towns to which patients could be sent.

There are two technical points I should like to raise. First, are the films made by the negative-positive process or on reversal stock? Secondly, how much work has been done on developing these films with "fine grain" developers, and have any methods of dye-toning been used to obviate grain?

Mr. R. M. Longman: It would be interesting to know whether the workings of the brain can be shown by means of the author's apparatus. He is at present only using the peak portion of one half of the wave; have not some experiments been made with a view to using both halves and thus increasing the efficiency? What is the power factor of the apparatus?

It is of interest to note the special arrangements, by means of interlocks, etc., to ensure safety to both patients and operators.

Dr. Russell J. Reynolds (*in reply*): In answer to Dr. Rowden, although it would be an additional advantage to be able to take pictures at any desired number of frames per second, yet the number of frames (submultiples of 50) possible at present is quite convenient. The synchronization is automatic and perfect. It would no doubt be a great advantage to use a screen giving an infra-red type of radiation, and I am already considering this. The apparatus in its present form costs £1 500 complete, and, in view of the fact that it provides a powerful X-ray unit apart from its use for cineradiography, the price appears to be reasonable. The actual cost of operation is probably not more than that of taking ordinary skiagrams.

Dr. Lees inquires how many frames a second I am taking. This necessarily depends upon the subjects, but varies from 6 in some alimentary subjects when the patient is big, to 25 in some chest or orthopaedic subjects.

In reply to Mr. Gurney's questions, the wavelength of X-rays is changed by the crystalline structure of the fluorescent screen into that of visible light; a green safelight is used in the dark-room; and there is no difficulty in securing perfect synchronization.

I am sorry that I cannot let Mr. Stuart know why a source of red light diminishes the afterglow, but it certainly appears to do so.

I can assure Mr. Craven that the heart is placed almost centrally in the body.

I wish to thank Prof. Hemingway for his appreciative remarks. The films were made by the negative-positive process. A very large number of developers have been experimented with, and one giving as fine a grain as possible consistent with adequate density has been chosen. No methods of dye-toning have so far been tried.

With reference to Mr. Longman's inquiry, the electrical efficiency is about 60 %.

DISCUSSION ON
"OPERATING PROBLEMS"*

BEFORE THE TRANSMISSION SECTION, 18TH MARCH, 1936

Mr. G. A. Crowson: I propose to deal with the problem of interruptions to the system, which problem I have divided into two sections: (1) Problems of communication in connection with control of supply on large interconnected h.t. systems. (2) The problem of reducing both the period and the number of interruptions to the supply.

To illustrate my remarks I will take the system of the Wessex Electricity Co. The territory covers an area of approximately 4 000 square miles (and extends over eight counties, from Oxfordshire in the north to Dorset in the south, and from Buckinghamshire in the east to part of Somerset in the west). It is for the most part rural, but there are several urban districts fed from the system. The total length of h.t. lines is 1 250 miles, and consists of five isolated groups. The four smaller groups comprise 290 miles, and the main system, to which I refer more particularly in my remarks on communication, comprises 960 miles. The length of the area from north to south is 140 miles. The maximum demand on the system for 1935 was 33 000 kW, and the number of units purchased was 95 250 000. There is no large central station within the area from which the system draws its supply, supplies actually being given from 11 points situated at various points on the network. For purposes of administration, the area is divided into twelve separate districts, served by management and engineering sections. The central control is at a point which is also the administrative centre of the area.

Consider first the problem of communication in connection with the operation of the system, the demands on that communication system, and how far they are being met. First, take the case of prearranged switching in connection with shutdowns on main lines for the purpose of carrying out repair work or routine testing. Usually such work can be planned ahead, and therefore the instructions for transferring supplies or for carrying out other work in the interests of continuity of supply can usually be arranged in advance. It is therefore generally possible for such instructions to be given by letter from the central control. The central control should direct operations in such cases, since a shutdown on a particular piece of main line may affect various sub-controls, and the actions of these sub-controls must be directed by one person.

Secondly, consider prearranged switching not affecting main lines but affecting only secondary lines. This operation is of a local character; it may not affect neighbouring districts, and can be carried out by the local control without the aid of direction from the central control. In this case there is little demand on the communication system.

Thirdly, consider emergency operations due to failures of supply. In such cases the greatest demands are made on the communication system. Take the case of a failure on a tapping supplying a few villages. If the failure occurs during the day, the local control officer may not be aware that anything has happened until, perhaps, a consumer informs the local office that his supply is off; the added duration of the interruption will then depend on the length of time taken in travelling to possibly a remote switching point and, in the case of a transient fault, renewing the fuse or closing the switch.

Take also the condition of a failure on a main line, which may affect several of the sub-control districts. If switching operations for this type of failure are to be under the control of the central control officer, then it is most desirable to have a private communication system in order to cut down to a minimum the time of communication, since it is often necessary to make several telephone calls in order to re-connect the supply to its normal state and, if a faulty section is involved, to isolate the fault.

Another condition, and probably the worst of all, is that of many failures over the system due to gales of wind. At times of severe gales the Post Office telephone system suffers in the same way as our own, so that when our demands on that system are greatest we find its service to be the least efficient, owing to falling trees and branches and to the various other troubles which result from gales. This trouble arises whether private telephone lines are in use or use is made of the normal system. Another difficulty may also arise: the local lines of the Post Office may be functioning well, but if a big area is disconnected owing to widespread failure, numbers of consumers ring up to ascertain what has happened to the supply, with consequent congestion on the exchanges.

I should like to mention one other condition—that of sectionalizing on a fairly long line in connection with the isolation of a permanent fault. This operation may involve travelling considerable distances to the switching points, and, since successive testing operations cannot take place until the switchman has carried out his several instructions and reported each switch operation to his local control, it is often necessary for him to travel many times backwards and forwards in order to report his various operations. Valuable time may therefore elapse before the supply on the sound portion of the network is restored. Telephone kiosks in the neighbourhood would of course be used if available, but in rural areas these facilities are not generally available. In the Wessex area we have endeavoured as far as possible to arrange switching operations so that minimum use is made of the telephone. We have no private telephone system.

* The discussion was opened by Messrs. G. A. Crowson and S. R. Siviour.

In operating a network there are two principles on which to work—the centralized system and the decentralized system. We have adopted a combination of both. The following gives a brief outline of our methods.

Consider, first, routine switching affecting only subsidiary lines. This is of a local nature, and the operations are therefore left to the local control officer. Routine switching affecting main-line supply is dealt with by the central control officer, and, since he can usually make his arrangements in advance, the arrangements are made by written instructions, copies being sent to other districts affected by the switching operations. Only in cases of urgency are instructions given by telephone. Emergency switching affecting main lines is more difficult to control owing to the distance covered by the trunk mains—about 150 miles—and the number of sources from which supply is taken. The method adopted is as follows: Each main-line substation is supplied with standing switching instructions covering as far as possible major interruptions affecting the particular locality. In the case of a main-line interruption, switching operations can be carried out without delay so long as the nature of the interruption is covered by the standing instructions. We have tried to make the latter as comprehensive as possible. The man responsible works to his instructions and telephones to the central control, so that the central control engineer can adjust the main control board.

Experience shows that this method of operation has, to a large extent, overcome the disadvantages attaching to the central control system, especially when no private telephone system is available. The men responsible for local switching are not specialists in this work since the majority of the substations are only attended part time, but it is found that, having been taught to operate to a set of instructions, they become more self-reliant.

In the case of widespread interruptions when telephone facilities are limited, the local control makes the best local arrangements possible for re-establishing the supply from the nearest available source. During a recent widespread gale the telephone system broke down, and in one district switching instructions were sent to the nearest grid point (28 miles) by road. Owing to fallen trees across roads the distance covered was 68 miles.

Communication is still a problem in cases of emergency. The nature of the problem suggests that wireless communication might offer a solution. I am informed that the Post Office have been approached, perhaps in a semi-official manner, but were unable to grant the facilities. I understand that the matter has received further consideration, however, and that we may hope for assistance from this service. When one considers that small fishing trawlers and aeroplanes are equipped with wireless, it does not appear too much to ask that the electricity supply industry—upon which the convenience of thousands of people depends—should be able to make use of such a valuable aid as wireless if it can be shown to assist materially in giving better service to the public.

The following figures giving the number of interruptions to supply during 1935 on the system referred to may be of interest: Gales, 68; lightning, 47; birds, 38; unknown causes, 99; failure of supply on other undertakers' system, 20; miscellaneous causes, 77; total, 349. Gales, lightning storms, and birds, are the worst offenders. Unknown causes are responsible for a fair number of interruptions, but there is very little doubt that many of these are due to birds. Allowing a proportion of unknown causes to birds, one may take 200 faults in the year as due to gales, thunderstorms, and birds. About 75 per cent of this 200 are transient faults.

In the case of main-line faults, the period of interruption is usually of short duration. On secondary lines, where the tapping points may be some distance from the centre of administration, the period of interruption is often serious. This problem has been recognized by the manufacturers, and has resulted in the development of the automatic-reclose switch. Five such switches have been on test for periods up to 15 months, controlling 128 miles of secondary lines. The following figures may be of interest: Number of faults dealt with, 42 (36 transient, 6 permanent); lightning, 12; unknown, 20; birds, 2; gales, 3; miscellaneous, 5.

With hand methods of switching, the period of interruptions on each of the 36 transient faults would have been a minimum of 20 minutes. With the aid of the auto-reclose switch, the interruptions were momentary only and consumers were not inconvenienced to any appreciable extent.

Another development recently introduced into this country is the Petersen coil. This piece of apparatus enables the h.t. supply to be maintained under earth-fault conditions. Two coils have been under test by the Wessex undertaking, and the following figures may be of interest. One coil has been in operation for 5 months, and has dealt with 20 faults. The number of combined phase and earth faults on which the switchgear operated on phase faults and the Petersen coil on earth faults—in other words, the number of supply interruptions—was 3. The number of earth faults on which the coil alone operated was 17; i.e. on 17 faults the supply was not interrupted. In one case, where a Petersen coil had been installed on an 11-kV cable system, when a fault developed the alarm buzzer attached to the Petersen coil operated. The supply voltage, however, remained undisturbed and, since it was inconvenient at the time to disconnect, the supply was left on for $2\frac{1}{2}$ hours. At the end of this period the supply was disconnected and the fault located. The cable was then re-connected under fault conditions for a further $7\frac{1}{2}$ hours. During a recent heavy gale, one coil operated 24 times over a period of 2 hours without interruption to supply, or inconvenience to consumers. On this occasion a flying branch was found to be hanging from the phase wire and swinging to earth.

Summarizing the foregoing, the total number of faults dealt with was 411. About 75 per cent of these affected secondary lines, and 75 per cent of that number were transient faults, giving a total of 240 transient faults on secondary lines. Petersen coils and auto-reclose switches dealt with 17 earth faults and 36 transient faults respectively, leaving 187 transient faults of long duration on those portions of the secondary network not at present fitted with either apparatus.

Mr. S. R. Siviour: The introduction of "live" line insulator testing as a routine operation has considerably

relieved the problem of maintaining the dielectric efficiency of 33-kV and 66-kV overhead lines. We are not here concerned with pollution (which is a condition obtaining on all insulators to a lesser or greater degree) but with the tracing of defects which are inherent to some part or parts of composite insulators and are usually ageing effects. These defects generally consist of minute cracks in the porcelain, mainly due to growth of cement or of metal components by hydration or corrosion; others may be due to inferior material or to external damage. A method of tracing these defects has been developed abroad, and experience in this country shows that it is suitable for multi-part insulators or for strings of the multiple-disc type at line operating voltages up to 66 kV.

It will be appreciated that if a crack develops in a pin-type insulator made up of two or three parts cemented together, a flashover may take place either under working voltage or due to transients. Similarly, if one or more units of a multiple string develops a defect, the stress distribution is seriously affected and the flashover value of the string greatly reduced. Prior to the adoption of "live" line testing, these defects could only be found by a pole-to-pole inspection. The object of the test is to check the potential gradient across the parts of a composite or multiple string of insulators.

The equipment consists of a 10-ft. fibre or bakelite insulated tube (made in two sections, screwed together) containing high-value resistances. For 33-kV lines, the top tube has a resistance of the order of 25 megohms and the lower tube of about 70 megohms, whilst for 66-kV lines the values are about 28 and 140 megohms respectively. The top end of the tube carries a metal contact prong, and a tough-rubber-protected trailing cable connects the bottom end of the tube to the instrument box. The latter contains a metal rectifier with d.c. microammeter and variable shunt resistance. The box is mounted on a spiked copper rod which provides the earth connection. The microammeter is calibrated 0 to 100, the variable shunt resistance being so rated as to give direct readings on the scale expressed as percentages of line voltage. The linesman having made contact with the line conductor, the resistance is adjusted to register 100 mA on the scale, and this represents the line voltage to earth. Contact is then made in turn with either the cement joints (in the case of multi-part pin insulators) or the metal caps (in the case of strings of suspension insulators). The difference between any two of these readings represents the percentage fall of potential between the corresponding points of contact.

The readings vary with the make and type of insulator, and also with the atmospheric conditions and the degree of pollution, but after a little experience basic values can be plotted. Insulators of the same type which are in sound condition will give the same fall of potential, but a defective insulator will give an entirely different reading, as the following examples of actual field tests show:—

VOLTAGE-DROP (PER CENT) VALUES FOR 3-PART PIN INSULATOR: LINE VOLTAGE, 33 KV

	Line	Top shed	Middle shed	Lower shed	Remarks
Normal readings ..	100	14	6	0	O.K.
Abnormal readings ..	100	72	30	0	Top shed defective
	100	20	16	0	Middle shed defective
	100	20	3	0	Lower shed defective

VOLTAGE-DROP (PER CENT) FOR CAP-AND-PIN INSULATOR CONSISTING OF THREE 10-IN. DIAMETER UNITS: LINE VOLTAGE, 33 KV

	Line	No. 1 (line)	No. 2	No. 3 (earth)	Remarks
Normal readings ..	100	43	20	0	O.K.
Abnormal readings ..	100	72	32	0	No. 1 (line end) defective
	100	43	39	0	No. 2 defective
	100	40	3	0	No. 3 defective

It will be noted that a defective unit considerably affects the normal stress distribution of the whole string. The operation is equivalent to a test across the metal plates of a condenser. A small amount of pollution appears to have little effect on results, provided there is no excessive humidity or surface moisture, but as the primary object is to find inherently defective insulators it is best for this purpose, for the safety of the operator, to confine the tests to fine, dry weather. The defective insulators, having been spotted by the "live" test, are removed at a convenient time and subjected to further tests. Results show that 90 per cent of insulators indicated by field test to be defective are unfit for further service.

Turning to the question of the fireproofing of cables, a fire which occurred in a main distribution substation as the result of the breakdown of a switch and which

caused considerable damage to certain outgoing 11-kV cables, directed attention to the need for protecting the cables against this hazard—particularly in main substations containing a number of switch units filled with oil or compound. Although the normal practice on the system concerned is to terminate cables in separate conduits terminating at floor-level below the switch, this was a special case where a cable trench was necessary, and the damage was greater than it might have been.

After several methods of protection had been investigated, the most successful was found to be a double lapping of 2 in. × $\frac{1}{8}$ in. asbestos tape with a good coating of silica paint applied overall. It will be understood that the outer servings had been first removed, leaving the armour wires, or, in the case of unarmoured cables, the lead sheath, clean and bright.

The practical test which led to the adoption of this method of protection was applied to a length of cable fixed in a normal manner, a sump around the cable at floor-level being filled with oil. After burning for 15 minutes the asbestos covering was doused with additional oil, and the sump again filled. The fire burned for 35 minutes, the whole of the cable being enveloped in flames. On dissection of the cable the asbestos tapes were removed intact, only the outer layer showing traces of exposure to flames. The armour wires were clean except for traces of compound which had exuded through from under the armour. The lead sheath was normal and the paper insulation unaffected. In other tests made with a bunsen burner applied in cycles on and off, the asbestos tape became incandescent, but no damage was done to the lead sheath or insulation. This test indicates that the method gives reasonable protection against concentrated heat.

It is important that the asbestos tape and silica paint should be free from harmful alkalies in order to avoid corrosion of the lead sheath where unarmoured cables are concerned, and as an additional precaution against this the sheath should be treated with a thin coat of suitable paint. After this a coat of silica paint is applied, followed by the asbestos tapes applied with 50 per cent overlap, and finally with a good coat of silica paint. A split welded-steel hood prevents oil flowing into the conduit, four small holes being drilled in the hood to provide ventilation to the conduit; the asbestos tape should be taken over the plumbed gland and over the neck of the steel hood. Where cable trenches are unavoidable, the trench should be filled with gravel and the protection applied as described above.

As regards cables in generating stations, the problem is more difficult, but in general the precautions should include the removal of all outer servings from cable, the provision of barriers between individual or groups of cables, and the closing of all holes through floors. The station problem is mainly one of segregation, in order to minimize the area of disturbance.

Mr. W. A. Turnbull: About a year ago we had a bad shutdown, caused by a short-circuit on the busbars. The trouble was that the isolator was mounted above the switch; the latter operated three times, which was sufficient to cause explosive gases to rise through the switch and collect in the isolator chamber. When we isolated in order to make a test, the minute capacitance spark exploded the gases, and everything inside the isolator chamber was carbonized, short-circuiting the whole of the busbars. It is desirable to arrange the busbars in such a way that one can get at them to isolate the switches. What I am doing is to fit round the solid-filled busbars collars which can be easily taken off so that the length of busbar can be disconnected and the switch isolated. In the case to which I have referred, it was $3\frac{1}{2}$ hours before we were able to get the supply on again.

Mr. W. J. H. Wood: Rural-area development increases the number of districts in which one must establish control of some kind. As the transmission system in an area grows, we find opportunities to interconnect single-circuit lines, and by that means we obtain the degree of reliability needed. We cannot prevent faults; the important thing is to re-establish the supply as quickly as possible after the fault has occurred, and this can be effected by proper local control. We need more local control, under the care of men who are in a position to act on their own initiative when their district is affected, provided they act in accordance with a predetermined scheme of operation laid down by a central controlling body.

A problem, greater than the operation of distribution, is that of switchgear. Our difficulty is a financial one; the cost of installing proper switchgear of adequate rupturing capacity is a very serious matter to a distributing authority. It is said that although the cost of generation has been brought down, the cost of distribution is still far too high; but the cost of distribution is bound to remain high owing to changed conditions brought about by the interconnection of generating sources.

Another problem I have very much in mind is the fire risk, already mentioned by Mr. Siviour. I feel it is our duty as engineers to take precautions to ensure fire isolation, in the case of buildings containing switchgear, by means of fire-resisting barriers and the like, and sectionalizing switchgear wherever practicable, to limit disturbances of supply that may result from fire.

Mr. W. S. Burge: The problem of telephony and communications in the distribution system of any particular undertaking is, of course, one of first importance and, unfortunately, one of great difficulty. It has already been amply stressed that in any such distribution system there must be numerous points of supply where attended substations are not available, and so a failure in telephone communications leaves the consumer "in the air."

On a fully organized system as is represented by the national grid, telephone communications, while still being of vital importance, are easier to maintain, because at most of the grid points there are power-station staffs available for dealing with any situation that may arise. Not only is this the case, but if the private-line telephone system should fail there are in addition the G.P.O. telephones to fall back upon.

Mr. A. H. Bennett: I should like to ask the openers of the discussion whether they have considered a regular, standardized form of issuing switching instructions. For many years now we have had issued by the control department a standardized form of instructions, stating

first of all the feeders or busbar sections which have to be dealt with, and whenever it is known that cleaning or repairs are going to be done these instructions are issued in good time. As far as possible, the name of the man who will be in charge of the work at each substation concerned is given and the men are further instructed that they must telephone to the control station before each operation, and before making alive again they must get confirmation that everything is clear.

Some years ago we instituted regular routine switching. On a certain day in each month (with the exception, perhaps, of times of very bad foggy weather, say in December or January) the whole of the 33-kV switches are operated on the feeders in turn. Every feeder switch is operated, first of all by means of a little trip on the protective gear, and then each means of automatic operation is tried in turn. The first operation is to trip the switch when the feeder is alive at both ends, and then the feeder switches are isolated and can be switched in and out as often as desired without constantly charging and discharging the feeders. The isolators, of which there may be one on each side of the switch, are opened. By this means we satisfy ourselves that the whole of the gear is in good working condition.

With regard to the testing rod with microammeter, etc., to which Mr. Siviour referred, our men had the greatest difficulty in getting at the insulators by means of this device. For examining the 4-piece insulators at the end of the stringing the apparatus might be useful, but there are not sufficient of those on our system to make it worth while.

With regard to the fireproofing of cables, there is no doubt that unless further precautions are taken we shall have more interruptions of supply as a result of a fire spreading to a neighbouring cable. Many years ago in substations where there was a possibility of fire we filled in the trenches with sand. Sand is very much better than earth, and it is easier to deal with.

Mr. J. H. C. Brooking: In America some two dozen of the most prominent supply companies combine to publish every year two little booklets, one giving a review of generating troubles and the other of operating troubles outside their generating stations. Surely there is room in Great Britain for an association which would deal only with troubles of the same kind, troubles which are continually becoming more frequent and taking new forms. If this Section can promote such a general discussion of troubles, it may be of considerable help to those engineers who have to deal with them.

Major T. Rich: Twelve years ago I visited a power system across the Channel of the kind that Mr. Crowson has described, and at the principal substation a carrier-current wire system was installed which gave every satisfaction. Such systems are used to-day on the 220-kV line from the South of France to Paris, and they have the advantage that they continue to operate even if the line is broken in a dozen places.

As regards the question of fire-fighting, at the Leipzig Fair a few days ago I noticed very few normal oil switches. The Germans and the Swiss, and to a large extent the French also, are saying to-day that, from the air-defence point of view alone, it is necessary as far as possible to dispense with the use of oil. Instead of the normal oil switches they have three types, the first using compressed air, the second water, and the third very little oil. The water switch is now available for such voltages as those mentioned by previous speakers, and the compressed-air switch is also on the market for voltages up to 220 kV. Another class of switch, which several manufacturers are making, is one where the function of the oil is to produce sufficient oil gas to put the arc out.

I should be interested to know what sort of automatic-reclose switches are now being used. Some depend on the current to reclose them, and others on weights.

The use of glass insulators is increasing. One of the advantages of this practice is that, if a puncture occurs on a glass insulator, normally a piece of glass is broken off and thus the damage can be seen from the ground.

Mr. F. J. Lane: When troubles occur on a distribution system, it is very important that the control operator should be able to find out quickly not only which switch has tripped, but also what kind of fault has initiated the tripping. For the latter purpose he has to turn to the protective-relay indications, and it is therefore important that such indications should be clearly visible and readily identified. Relay indicators as manufactured are not all of the same type, some being semaphores which come into view when the relay operates, others revealing a white or coloured surface, and others again causing a coloured plate, normally visible, to disappear from view. Many relays contain brightly polished or light-coloured parts, distracting the eye from the indicator. There are designs of relay in which the indicator is relegated to a dark corner of the case, so that one has to peer into the cover to observe the indicator position. For observation purposes the indicator should be as prominent as possible when operated, and its position, its "indication," and its relationship with other visible components, should be carefully considered with this end in view.

A further point concerns the marking of the relay function, as it is this which tells the operator what fault has occurred. Except to the protective-gear expert the manufacturer's "type letters" or catalogue reference offer no useful guide, and a great many misunderstandings might be saved if the relay label were to show in large type the function of the relay—"EARTH FAULT RELAY," "OVERCURRENT RELAY," "IMPEDANCE RELAY"—with all other data given in much smaller letters.

With increased centralization of control, the control engineer often has to obtain information from operators with no specialized knowledge of protective relays, and anything which can be done to ensure rapid observation and accurate reports will greatly assist the resumption of normal conditions after faults have occurred.

Mr. W. Fennell: In connection with Mr. Crowson's communication problem I would suggest the device of having a secret number on the telephone system. The advantage of this is that when things go wrong the line is not blocked by the public, though it may be blocked by the supply undertaking's staff ringing up from various parts of the area to know whether they can be of any help.

With regard to priority for repairs on the telephone, about 10 years ago I took this matter up with the Post

Office, and they told us that we could not have priority. (The only "private" people who had it, so far as I could discover, were doctors.) I then took the matter up with the Electricity Commissioners, and they negotiated with the Post Office, with the result that we were put on the priority list. Nowadays any supply undertaking has the right to be placed on the priority repair list for the district which it serves.

With regard to underground circuits, I have one very important communication circuit on my system. It is a remote-reading ammeter, which shows us in Northwich town what the bulk-supply ammeter is reading $2\frac{1}{2}$ miles away in the bulk-supply substation. We have batteries in Northwich, and we can control the maximum demand and so reduce the maximum demand on the power company if we know the load from minute to minute. As it was essential that this circuit be reliable I asked the G.P.O. to provide an underground circuit. They eventually offered a second overhead circuit at an extra charge to be used when the first failed. Finally we arranged for a single circuit, of 100-lb. wires, and have had very little trouble.

ANNUAL DINNER, 1937

The Annual Dinner of The Institution was held at Grosvenor House, Park Lane, London, on Thursday, 4th February, 1937, when the President, Mr. H. T. Young, presided over a gathering numbering 1 015. Among those present were: The Rt. Hon. the Viscount Falmouth; The Rt. Hon. Lord Pentland; The Rt. Hon. Lord Stonehaven, P.C., G.C.M.G., D.S.O., LL.D. (*President, Institution of Naval Architects*); The Rt. Hon. Lord Macmillan, P.C., G.C.V.O.; The Rt. Hon. Lord Rutherford of Nelson, O.M., D.Sc., LL.D., F.R.S. (*Chairman of the Advisory Council, Department of Scientific and Industrial Research*); The Rt. Hon. Lord Eltisley, K.B.E. (*President, British Electrical Development Association*); Admiral of the Fleet Sir A. Ernle M. Chatfield, G.C.B., K.C.M.G., C.V.O. (*First Sea Lord and Chief of Naval Staff, Admiralty*); Air Vice-Marshal Sir Philip Game, G.B.E., K.C.B., K.C.M.G., D.S.O. (*Commissioner of Police of the Metropolis*); Sir Alexander Gibb, G.B.E., C.B., F.R.S. (*President, Institution of Civil Engineers*); Vice-Admiral Sir R. G. H. Henderson, K.C.B. (*Third Sea Lord and Controller, Admiralty*); Sir Frank E. Smith, K.C.B., C.B.E., D.Sc., LL.D., F.R.S. (*Secretary, Department of Scientific and Industrial Research; Director, National Physical Laboratory; Secretary, Royal Society*); Sir Edward Crowe, K.C.M.G. (*Comptroller-General, Department of Overseas Trade*); Sir Cuthbert Wallace, K.C.M.G., C.B. (*President, Royal College of Surgeons*); Sir William H. Bragg, O.M., K.B.E., F.R.S. (*Honorary Member, I.E.E.; President, Royal Society; Fullerian Professor of Chemistry, Royal Institution*); Sir Thomas Gardiner, K.B.E. (*Director-General, Post Office*); Sir Arnold B. Gridley, K.B.E., M.P.; Sir Noel Ashbridge (*Member of Council*); Sir John Brooke, C.B. (*Vice-Chairman, Electricity Commission*); Sir Geoffrey Clarke, C.S.I., O.B.E. (*President, Association of British Chambers of Commerce*); Sir H. Nigel Gresley, C.B.E., D.Sc. (*President, Institution of Mechanical Engineers*); Sir Montague Hughman; Sir George Lee, O.B.E., M.C. (*Vice-President, I.E.E.; Engineer-in-Chief, Post Office*); Sir Archibald Page (*Past President, I.E.E.; Chairman, Central Electricity Board*); Sir John H. Parsons, C.B.E., F.R.C.S., F.R.S. (*President, Royal Society of Medicine*); Sir Leonard Pearce, C.B.E., D.Sc.; Col. Sir Thomas F. Purves, O.B.E. (*Past President*); Sir Maurice Simpson, C.S.I.; The Hon. Arthur Howard, J.P. (*Mayor of Westminster*); Mr. Ll. B. Atkinson (*Past President; Honorary Member*); Mr. W. J. Bache (*Vice-President, Incorporated Municipal Electrical Association*); Mr. J. R. Beard, M.Sc. (*Member of Council*); Mr. H. R. Beasant (*Hon. Secretary, Western Centre*); Mr. A. Berkeley (*Chairman, British Electrical and Allied Industries Research Association*); Mr. A. C. Bostel (*Hon. Secretary, Sheffield Sub-Centre*); Mr. E. S. Byng (*Member of Council*); Mr. C. Augustus Carlow (*President, Institution of Mining Engineers*); Mr. L. H. A. Carr, M.Sc.Tech. (*Hon. Secretary, North-Western Centre*); Mr. Roger N. Carter, M.Comm. (*President, Institute of Chartered Accountants*); Mr. F. H. Clough, C.B.E. (*Past Chairman, South Midland Centre*); Mr. F. W. Crawter (*Honorary Treasurer*); Prof. J. A. Crowther, M.A., Sc.D. (*President, British Institute of Radiology*); Mr. A. Cunnington (*President, Illuminating Engineering Society*); Mr. M. H. Damme (*Acting President, Koninklijk Instituut van Ingenieurs*); Mr. J. M. Donaldson, M.C. (*Past President, I.E.E.; President, Incorporated Association of Electric Power Companies*); Dr. S. F. Dorey (*Chief Engineer Surveyor, Lloyd's Register of Shipping*); Mr. H. M. Drake (*President, Electrical Contractors' Association*); Mr. J. F. Driver (*Hon. Secretary, East Midland Sub-Centre*); Dr. P. Dunsheath, O.B.E., M.A. (*Chairman, Transmission Section*); Mr. R. N. Eaton (*Hon. Secretary, Irish Centre*); Dr. W. H. Eccles, F.R.S. (*Past President*); Mr. J. Chuter Ede, J.P., D.L., M.P. (*Chairman, Surrey County Council; Chairman, London and Home Counties Joint Electricity Authority*); Lieut.-Col. K. Edgcumbe, T.D. (*Past President*); Mr. E. J. Elford (*Chairman, British Standards Institution*); Mr. A. P. M. Fleming, C.B.E., M.Sc. (*Vice-President*); Prof. C. L. Fortescue, O.B.E., M.A. (*Member of Council*); Col. H. Cecil Fraser, D.S.O., O.B.E., T.D. (*Past Chairman, North Midland Centre*); Mr. F. Gill, O.B.E. (*Past President*); Mr. W. J. McC. Girvan (*Hon. Secretary, Northern Ireland Sub-Centre*); Mr. W. T. Halcrow (*Chairman, Association of Consulting Engineers*); Mr. J. S. Highfield (*Past President*); Mr. W. E. Highfield (*Vice-President*); Mr. A. G. Hiscock (*Hon. Secretary, Hampshire Sub-Centre*); Mr. Frank Hodges, J.P. (*Central Electricity Board*); Mr. C. Holden, Litt.D., F.R.I.B.A. (*Vice-President, Royal Institute of British Architects*); Mr. H. Hooper (*Hon. Secretary, South Midland Centre*); Mr. P. V. Hunter, C.B.E. (*Past President*); Mr. J. M. Kennedy, O.B.E. (*Past President*); Mr. Stephen Lacey, B.Sc. (*President, Institution of Gas Engineers*);

Mr. E. M. Lee (*Member of Council*); Brig.-Gen. R. F. Legge, C.B.E., D.S.O. (*Member of Council*); Mr. E. C. McKinnon (*Past Chairman, North-Western Centre*); Mr. M. M. Macqueen (*Chairman, Radio Manufacturers' Association*); Dr. E. Mallett (*Chairman, Wireless Section*); Mr. S. W. Melsom (*Member of Council*); Mr. W. M. Mordey (*Past President; Honorary Member*); Brig.-Gen. Magnus Mowat, C.B.E. (*Secretary, Institution of Mechanical Engineers*); Mr. F. E. J. Ockenden (*Member of Council*); Mr. W. Parry, M.Eng. (*Hon. Secretary, Mersey and North Wales (Liverpool) Centre*); Mr. Clifford C. Paterson, O.B.E. (*Past President*); Dr. Robert H. Pickard, F.R.S. (*President, Institute of Chemistry*); Mr. G. L. Porter (*Chairman, North-Western Centre*); Mr. H. B. Poynder (*Hon. Secretary, North-Eastern Centre*); Mr. E. A. Reynolds, M.A. (*Chairman, South Midland Centre*); Mr. R. Richards [*Hon. Secretary, West Wales (Swansea) Sub-Centre*]; Dr. A. Russell, M.A., D.Sc., LL.D., F.R.S. (*Past President; Hon. Member*, 1937); Mr. H. Shaw (*Hon. Secretary, Tees-side Sub-Centre*); Mr. G. F. Shotter (*Chairman, Meter and Instrument Section*); Mr. S. R. Siviour (*Chairman, North Midland Centre*); Mr. W. R. T. Skinner (*Hon. Secretary, North Midland Centre*); Mr. Roger T. Smith (*Past President*); Mr. J. W. Spark (*Chairman, Western Centre*); Mr. Charles P. Sparks, C.B.E. (*Past President*); Mr. Sydney Tatchell, F.R.I.B.A. (*President, Building Industries National Council*); Mr. C. S. Taylor (*Past Chairman, China Centre*); Mr. J. W. Thomas, LL.B. (*Member of Council*); Prof. W. M. Thornton, O.B.E., D.Sc., D.Eng. (*Past President*); Mr. R. J. Tugwood (*President, Chartered Institute of Patent Agents*); Mr. V. Watlington, M.B.E. (*Member of Council*); Mr. O. C. Waygood [*Past Chairman, Mersey and North Wales (Liverpool) Centre*]; Mr. C. R. Westlake (*Member of Council*); Mr. F. C. Winfield, M.Eng. (*Past Chairman, North-Eastern Centre*); Mr. R. S. Wood (*Principal Assistant Secretary, Technological Branch, Board of Education*); Mr. W. J. H. Wood (*Member of Council*); Mr. C. S. Wright, O.B.E., M.C., M.A. (*Director of Scientific Research, Admiralty*); Mr. Johnstone Wright (*Vice-President*); and Mr. P. F. Rowell (*Secretary*).

The toasts of "His Majesty the King," and "Her Majesty the Queen, Her Majesty Queen Mary, and the other members of the Royal Family," were proposed by the President and were loyally received.

The Rt. Hon. Lord Macmillan, P.C., G.C.V.O., in proposing the toast of "The Institution," said: "The success of this Institution, which it is my privilege to ask you to toast to-night, is obviously something that has already been accomplished. One cannot but feel how very recent it all is. Your Institution began only within the lifetime of many men still alive. It began in 1871 with a small coterie of those interested in what was then only the dawn of electricity, and now it numbers over 17 000 and includes members resident in 98 countries. That is truly a very great achievement. When I see how recent it is, I think of a very interesting piece of history which I learnt some time ago. Sir Francis Ronalds, a great inventor, who gave a library to your Institution, proposed an electric telegraph to the Admiralty in 1818. He was told that 'telegraphs of any kind are now totally unnecessary and no other than the one now in use (which was the old mechanical semaphore) will be adopted.' Surely a declaration worthy to stand beside another made by the Admiralty in 1830, when they declared that they felt it their bounden duty to discourage the introduction of steam as calculated to strike a fatal blow at the naval supremacy of the Empire. What is so interesting about it is this. You see how things which at their introduction are doubted—like the railways and so many other facilities of the country—in the course of a few years become of tremendous benefit, and in the case of electricity one of the greatest benefits which the world has ever known and which is utilized and appreciated by no Department of the State more than by the Admiralty itself.

"I look upon you as almost magicians. You are the modern prototypes of the old alchemists, because you deal with something you know nothing about, no one having yet been able to explain what electricity really is. But what it does is a different matter, and there you have been able by your work, both in the laboratory and in practice, to benefit humanity as have probably few other great discoveries. The scope and extent of your work is amazing. You warm us in winter and cool us in summer. You transport us from one part of the world to another. You take our communications by telegraph and telephone. You provide us in the evening with wireless, and in our moments of pain and distress you come to the aid of the medical profession. There is nothing too big, and nothing too small, to enlist your interest; for in *The Times* this morning I read that two insulated sausage vans have just been built at the works of the Great Western Railway for working on fast passenger trains. Each van has its own electrical unit. This operates the interior lighting and an electric fan which draws air into the van over an ice tank and maintains, through a duct, a free and even circulation.

"I have read the last Annual Report of your Council and I am amazed at the variety of your interests. I specially commend your interest in research, but I would ask you to remember that the word 'research' is often used in these days for what is not research at all. Research in the true sense of the word—research into the problems awaiting solution, and undertaken by men who are competent for the work—is amongst the greatest services that can be rendered; and I know how devoted your Institution is to that great branch of administration.

"Lastly, I must not leave out of account your Benevolent Fund. Some of us must fall by the way and in the brotherhood of a profession it is right that we should remember those less fortunate than ourselves.

"I thank you on behalf of the community for the great service your Institution renders to all, and I conclude by asking you to rise and drink to the success of your Institution. The toast is 'The Institution of Electrical Engineers' coupled with the name of the President."

The President, in responding to the toast, said: "It taxes greatly the language of appreciation to reply to such generous remarks as those of Lord Macmillan. He is, as many of you know, Chairman of the Court of the London University, whose new building is now in course of construction. As electrical engineers we are pleased to note that the new building is to be one of the most adequately equipped electrically in this country. Nearly

all its services will be provided by electricity. We are also pleased to have with us the architect for the building, who is here representing the R.I.B.A. as its vice-president. I will add that we are more than satisfied with the electrical installation in the R.I.B.A.'s own building, for, in addition to a number of other electrical services, an electrode boiler has been installed for the heating.

"In connection with Lord Macmillan's reference to the size of our Institution I would say that we have formed 17 Local Centres and Sub-Centres, and we feel that they are of great importance to The Institution. Two of them are in South America and China respectively, and we co-operate there with local branches of the Institutions of Civil Engineers and Mechanical Engineers. That co-operation is very important, and I think that it would be to the benefit of British industry if we could work a little more closely together in other centres.

"No industry has given more attention to research than the electrical industry. This research work has been of great assistance to industry in general, including the public utility undertakings—electricity supply, telecommunications, and broadcasting. The electric supply industry is developing so rapidly that last year 800 000 new consumers were connected in England and Ireland, and the increase in the number of units sold was approximately 15·1 %; in this connection it is interesting to note that in the London Power Co.'s Battersea station there was generated last year more electricity than was sold in the whole of the United Kingdom in the year when King George V came to the throne 26 years ago. Not only are the supply undertakings seeing that industry gets the power it needs, but they are also taking care that the poorer people of the country are able to obtain for a few shillings per week an electric supply for light, heat, and radio. The electric supply industry is doing this in a way that is unequalled in any other country in the world.

"Turning now to the Post Office, we are delighted to know that its Chief Engineer has this week had a well-deserved honour conferred on him by His Majesty the King. We now have something like $2\frac{3}{4}$ million telephones installed, half a million having been added last year; whilst there are no less than 8 million wireless licence-holders.

"The great future of electricity lies in the study of its utilization. There are at least 100 electrical applications to which I could refer.

"As the subject of the nation's health is very much to the fore to-day, I should like to say that greater co-operation is needed between ourselves and the medical profession, particularly in connection with the use of electricity in the operating theatre.

"Another important matter is air-conditioning. This is advancing very rapidly, and I am delighted to know that it will shortly be applied to this room so that provision will be made for no less than 15 changes of air per hour.

"Another matter to which I should like to draw attention is the insanitary dustbin that we see on our pavements. It will not be long, I think, before the electrical industry will have a great surprise for, and be able to assist, the medical officers of health and sanitary engineers by providing an alternative to the present antiquated system of garbage removal.

"With regard to the Coronation, the public will expect a great deal of electrical illumination and they will not be disappointed. I ask electrical engineers all over the country to collaborate as far as possible with the architects, so that any special lighting is carried out with dignity. In the presence of the First Sea Lord I suggest that a few warships—they need not be very large and might include flying-boats—be brought up the Thames and illuminated for the Coronation period. The embankment and bridges should also be illuminated and some illuminated fountains fitted in Hyde Park.

"May I say, finally, that ours is a great industry, whose growth has been phenomenal and whose potentialities for public service are so immense as to be beyond our powers of imagination. We are in the position of being a little ahead of public knowledge, and even of public opinion. It is a serious responsibility—that of bringing nations and peoples to a willing sense of what electricity can do for them. From what I know of the men who are associated in that task I can say that it is one which they will face courageously and worthily discharge. Lord Macmillan, I again thank you for the kind words you used in your speech and I thank everyone here for the manner in which they received them."

Mr. Clifford C. Paterson, O.B.E. (*Past President*) then proposed the toast of "Our Guests," to which **The Rt. Hon. Lord Stonehaven, P.C., G.C.M.G., D.S.O., LL.D.** (*President, Institution of Naval Architects*) and **Mr. Sydney Tatchell, F.R.I.B.A.** (*President, Building Industries National Council*) responded.

A reunion was subsequently held.

HISTORY OF THE INSTITUTION

The Council have given authority for a history of The Institution to be written, and Mr. Rollo Appleyard has undertaken to prepare the book.

A great deal of relevant material is already in the archives of The Institution, but it is felt that there must be many members and others who have in their possession information, or can recall facts, which might be of assistance to Mr. Appleyard in making the work complete so far as possible. It is requested, therefore, that those who have such information should write to Mr. Appleyard, c/o the Secretary of The Institution.

ELECTIONS AND TRANSFERS

At the Ordinary Meeting of The Institution held on the 11th March, 1937, the following elections and transfers were effected:—

Elections

Associate Members

Davis, Robert, M.Sc.
Foster, Samuel Slack.
Francis, Victor James, B.Sc.
Fraser, Robert Whyte, B.Sc.
Hunt, Rowland Henry.
Keays, Hastings de Jersey.
Kensington, Cuthbert Babington, M.C.
Lee, Alan, M.A.
Morgan, Algernon Feltham.
Roberts, Vernon Madoc, B.Sc.
Scott, James Scott.

Companions

Dean, John Norman.
Studholme, Richard Home.

Associate

Swinbank, Robert Peel.

Graduates

Blackford, Harold George.
Brown, William.
Brünniche, Erling Aage.
Clarke, Percy.
D'Souza, Franklin.
Garvey, William Edwin.
Gray, Robert, B.Sc.Tech.
Harrison, William James D.
Higgs, George James.
Margary, Harry Herbert, B.A.
Mellor, Harry Whitaker.
Piper, Ernest Frank.
Robinson, Henry Robert.
Rowsell, William Charles.
Townsley, Jonathan.
Weller, Cyril William.
Wilson, Charles Gillam.

Students

Adams, Bernard Leslie.
Aitken, Robert Muirhead.
Alag, Sarbindar Singh.
Allsop, Arthur Geoffrey.
Antram, Alfred Harry.
Appuhamy, Jayakody Don F.
Arakiel, Sarkies George.
Ardis, Robert Frederick.
Arup, John Dahl.
Assenheim, Joseph Philip.
Austin, George Nicol.
Bailey, John Claude.
Ball, Herbert.
Bamford, Harry.
Barette, Kenneth.
Barnes, John.
Bennell, Frank Tasman.
Biddle, Gordon.
Billings, John Alfred.
Blewett, Frank Edmund.
Blood, Walter Roy.

Students—continued.

Bowers, Robert.
Brady, Lawrence.
Brassington, Arthur Gerald.
Browning-May, Richard Eugene.
Buck, James.
Burns, Islay Douglas H.
Burra, James Patrick M.
Burton, Herbert Ernest.
Butcher, Ernest Thomas.
Butt, Desmond Lorrain.
Callf, James.
Campbell, Charles Francis.
Capes, John Philip.
Casperd, Stanley George.
Charlesworth, William Richards.
Chatterjee, Amiya Kumar.
Chokkanadhan, T. S., B.E.
Claxton, Sydney George.
Cocker, Henry Lawrence.
Cole, Richard Alexander.
Collett, Bernard Furnival.
Cook, Edgar FitzInman.
Cosgrove, John.
Cowley, Herbert William L.
Craig, Robert Allan M.
Cross, Cyril Austin.
Culley, Claude.
Curry, Wilfred.
Dain, Christopher.
Damodaran, G. Rangaswamy.
Davies, Alfred Gerald.
Davies, Benjamin Daniel.
Davies, Thomas George.
Davis, Herbert Lister.
Dickinson, Fred.
Dobell, Leslie Thomas F.
Dodds, Joseph Edward.
Dolman, Frank Kenneth.
Easton, Kenneth John.
Eckersley, Norman Gregson.
Edwards, George.
Every, Frank Robson.
Ewing, James David.
Eyton, John William T.
Farmer, Jesse Tinton.
Ferguson, Anthony Alexander.
Fernando, Waranakula Lodwin.
Field, Walter Francis.
Fisher, Arthur John M.
Fouad, Mohamed Ez.
Francis, Hugh Cameron.
Francis, Stanley Walter.
Freer, James.
Gentles, Ernest Robert.
Ghare, Yeshwant Bhaskar.
Gibson, Clarance.
Gildea, Patrick James H.
Goddard, Norman Sidney.
Gordon, Albert Percival.
Gould, William Frederick C.
Graneek, Maurice.
Green, George Wilson.
Grierson, Richard Alan.
Grieve, Daniel McLay.
Griggs, John Carlick.
Haigh, Alan Hattersley.
Halls, Victor John.
Harmsworth, John Alfred.
Harrington, William Barratt.
Harris, Robert John, B.Sc. (Eng.).
Haslock, Edwin Jarvis.
Hawke, Arthur Edgar.
Hawkins, Walter Gilbert.
Heath, James Henry.
Henderson, Jack.
Hetreed, Michael James.
Heward, Sydney Cyril.
Hewitt, Alfred Gordon.
Hiles, Eric James.
Hill, Arthur Selwyn.
Hilton, James Whittaker.
Hitchcock, Cornelius Mathew F.
Holberton, Adam Joseph.
Holland, Philip.
Hope, Leslie.
Howie, Robert Campbell.
Hudson, George Kenneth.
Ingram, Thomas Parker.
Jackson, Harold.
James, Charles Kenneth.
James, Herbert Henry.
Jones, Frank.
Jones, John Horace G.
Jones, Lewis Blount.
Jones, Sydney Birkhead.
Kapus, Erwin Esteban, B.Sc.(Eng.).
Karanjia, Pheroze Behram.

Students—continued.

Kerr, William Donald.
Khan, Dost Mohammad, B.A.
Kinder, Arthur Thomas.
King, Harold Reginald.
Knight, Leslie Charles.
Knight, William Bradley.
Lawson, Edred.
Lee, Horace Arthur.
Lee, Robert Max.
Lister, Henry Stuart.
Locke, Cyril Frederick.
Long, Henry Walker N.
Luther, Roy Kenneth.
Luthra, Satya Pal.
Lysons, Horace.
Macdonald, Roderick Ian.
Mackay, Neil John.
Maginnis, Arthur John.
Manning, Cyril Edwin.
Marden, John Harold.
Marriott, Francis George.
Marriott, Ronald Walter.
Marsh, Maurice Gascoigne.
Martin, Richard Harold G.
Michaelson, Kenneth Bertram.
Miller, Arthur.
Minwala, J. D.
Montgomery, Philip Albert.
Moore, John Franklyn.
Morgan, Clifford Henry.
Morrison, Sidney Robert.
Munro, Gordon Edwin.
Murray, Frederick Herbert.
Nanra, Jogindar Singh.
Nelson, Thomas Eric S.
Newby, Thomas Hobbs.
Newey, Gordon William J.
Nicholas, Ronald Frank.
Nicholson, Felix Temple.
Nicholson, George Galloway.
Nivasnanda, Wunlop.
Noble, Gordon.
O'Dell, Albert George.
Parke, Edward Ghymer.
Pearce, Albert John.
Pearce, Philip Henry.
Penty, John.
Peretz, Louis.
Perry, Arthur.
Phillipson, Stephen Milner.
Porter, Harold.
Powley, Reginald Arthur.
Preston, Stanley.
Pritchard, Stephen Percival.
Pryor, Frederick John.
Purchase, Harry Zander.
Purves, Ronald Marshall.
Raby, Charles Henry.
Raimondo, Anthony.
Rajagopalam, Ramanatha.
Rao, Nadella Raghavendra, B.Sc.(Eng.).
Reddy, Chintalpani Sudersan.
Reid-Jones, John William.
Rew, Wilfred Leonard.
Rhodes, George Dewhirst.
Richards, Sydney Bennett.
Roberts, Cyril Wilfrid.
Robertson, Alfred Peter.
Robertson, James Young.
Roden, William Thomas C.
Rogers, Robert William.
Rose, Raymond.
Ross, John Prentice.
Rowland, David.
Russell, Graham.
Ryder, Donald Henry.
Ryder, Lionel Ralph.
Satchell, Edward William J.
Schaffer, Paul.
Scorgie, Guy Craig.
Scott, Aethelstane Bodley.
Scott, William Wilson.
Seabrook, Leonard.
Seddon, Edwin.
Shipp, Guy Emmerson.
Simpson, Kenneth George.
Small, Donald William F.
Smiley, Hugh.
Smith, George Laurence.
Smith, Herbert Samuel.
Smith, James Newton.
Spilling, Eric George.
Srinivasan, Kadaba Yajaman.
Stevens, Philip Frederick.
Stewart, Hugh McKenzie.
Stokes, Morris Amos.
Story, Edward.
Suckling, Maurice Patrick.
Sutton, William Verdun.
Tandon, Maharaj Krishna, B.A.
Taylor, Arthur Joseph W.
Taylor, James Geoffrey.
Taylor, Robert Douglas.

Students—continued.

Taylor, Russell.
Thornton, Gerald Roberts.
Threlfall, Andrew James C.
Thwaite, Ben Eli.
Todd, William Norman.
Tozer, James Johnstone.
Travis, Leonard Kirkbride.
Trevelyan, Robert James.
Trott, Ralph Henry.
Troughton, Frederick Arthur.
Turk, John Thorp.
Turner, William Edgar.
Viegas, Jose Francis.
Visvanathan, Thatipatri Venkatasubramania.
Walford, Lancelot Desborough.
Walker, John Egan.
Walshe, Luke Charles.
Ward, Jack.
Welford, James.
Westgate, Thomas Frederick.
Whaley, Norman Sheffield.
White, Harry William N.
White, Maurice John H.
Whitehouse, Cecil Frederick.
Whitton, George Alexander.
Williams, Thomas Norman.
Willis, Michael Douglas.
Willoughby, John.
Wilson, Joseph Shevlin.
Winram, Norman.
Wood, Arthur James.
Wood, Geoffrey Hadfield.
Woodrow, Victor Harold.
Woodward, Harry.
Workman, Albert Henry.

Transfers

Associate Member to Member

Aldridge, Arthur John.
Tubini, Bernard A.

Associate to Member

Yeaman, Charles Henry.

Associate to Associate Member

Curd, David Alfred G.
Patmore, Sydney John.
Spence, Harold Cruickshank.

Graduate to Associate Member

Barnett, Henry Edgar, M.Sc.
Bartlett, Herbert Edward.
Bedford, Geoffrey Francis, B.Sc.
Bishop, William Russell.
Bradley, Basil Dermot, B.Sc.
Caton, George.
Cook, Arthur, B.Sc.
Dawson, Alfred John, M.Sc.
Dempster, David, B.Sc., Ph.D.
Farthing, Geoffrey Arthur.
Gould, Charles Thomas.
Hutton, Frederick Montgomerie G., B.A.
Love, Kenneth George.
Lucas, Frank Newton, B.Sc.
Mare, Arthur John, B.Sc. (Eng.).
Megaw, Eric Christopher S., B.Sc.
Moss, John Lawrence.
Porter, John Ernest.
Slade, William Charles, B.Sc.(Eng.).
Tatton, Eric.
Turner, Dennis Round, M.Eng.

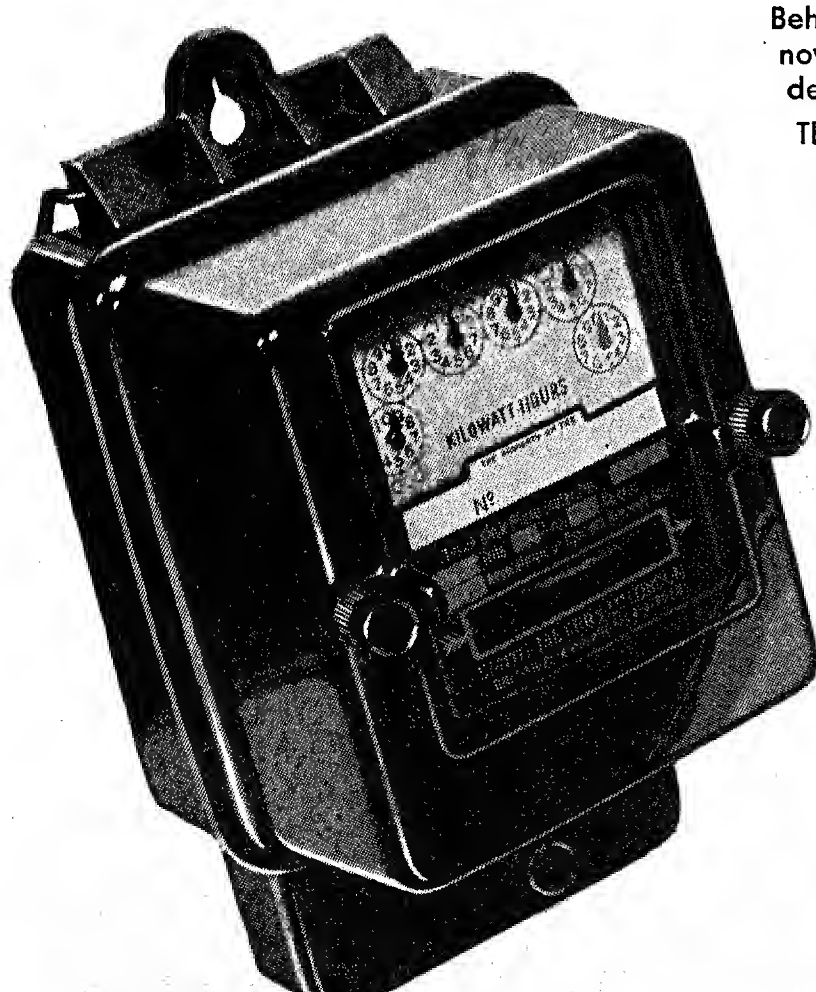
Student to Associate Member

Blair, David Charles.

Student to Associate

Parr, Bernard Arthur.

and behind it all-



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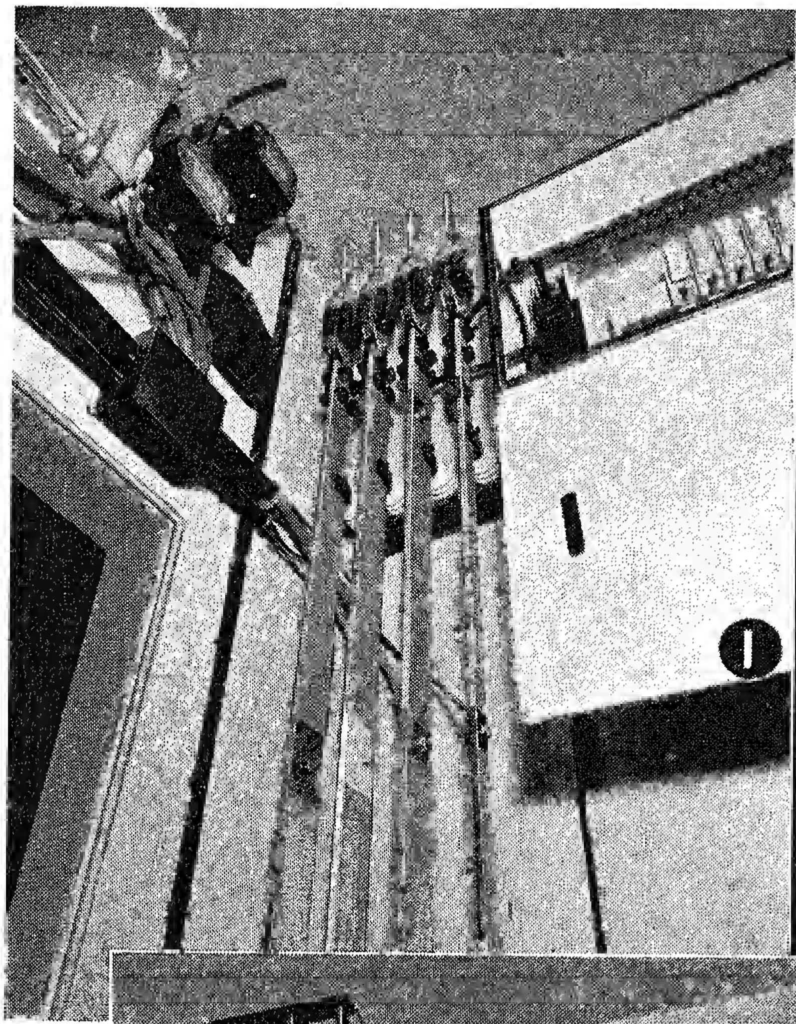
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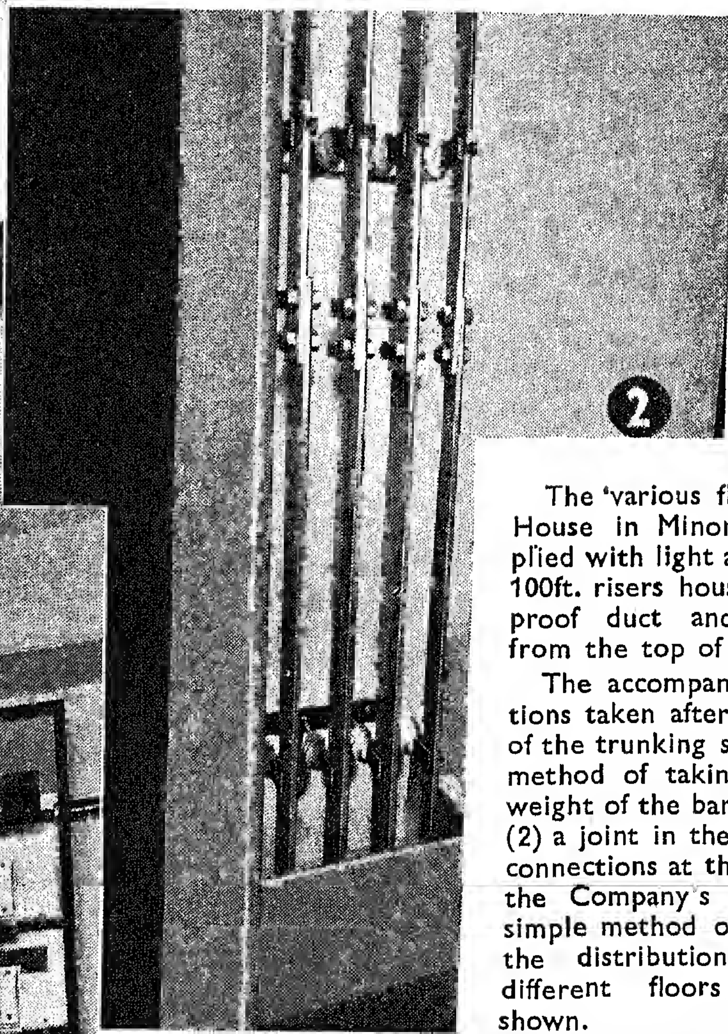
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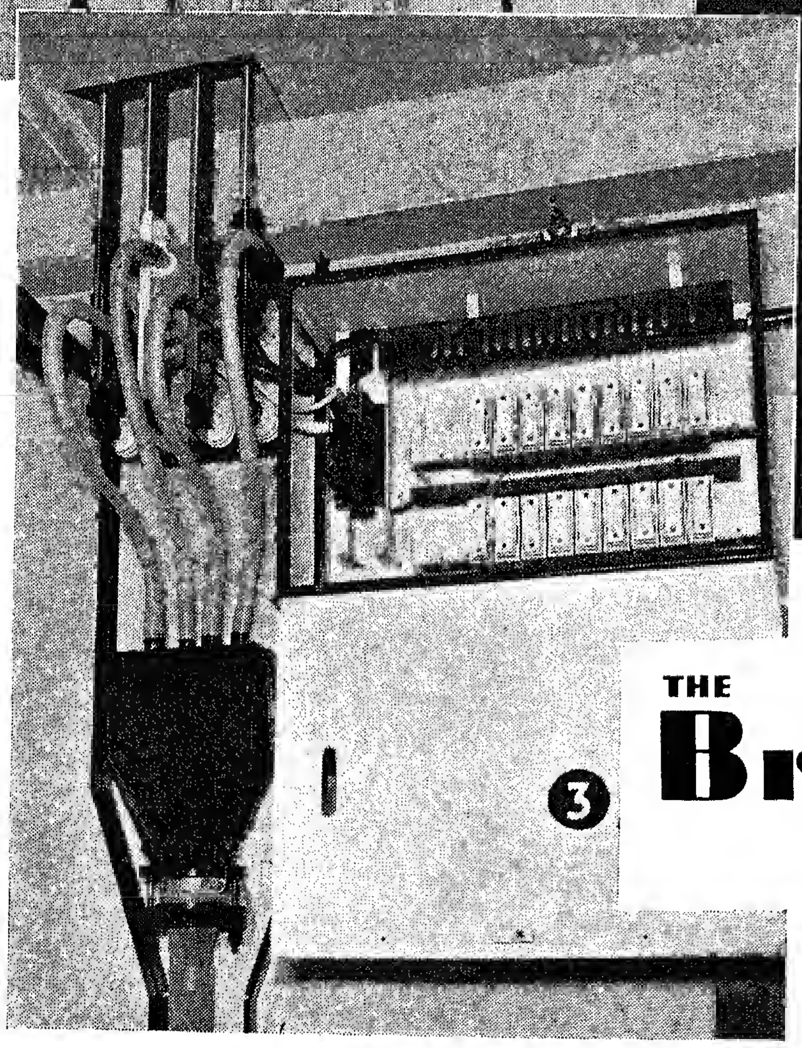
3

The various floors at Ibex House in Minories are supplied with light and power by 100ft. risers housed in a fireproof duct and suspended from the top of the building.

The accompanying illustrations taken after the removal of the trunking show: (1) the method of taking the whole weight of the bars at the top; (2) a joint in the run; (3) the connections at the bottom to the Company's mains. The simple method of tapping to the distribution boxes at different floors is clearly shown.

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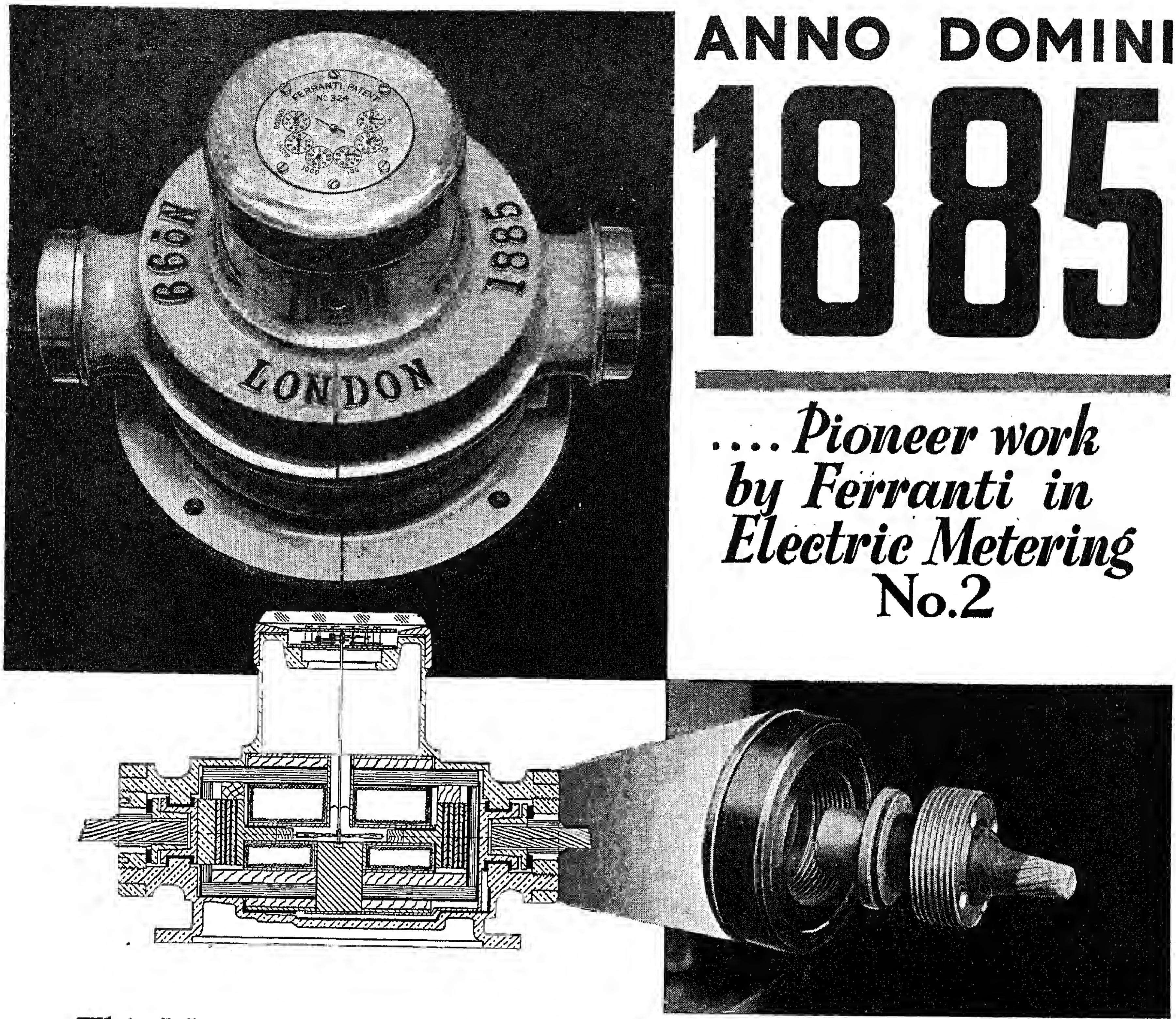

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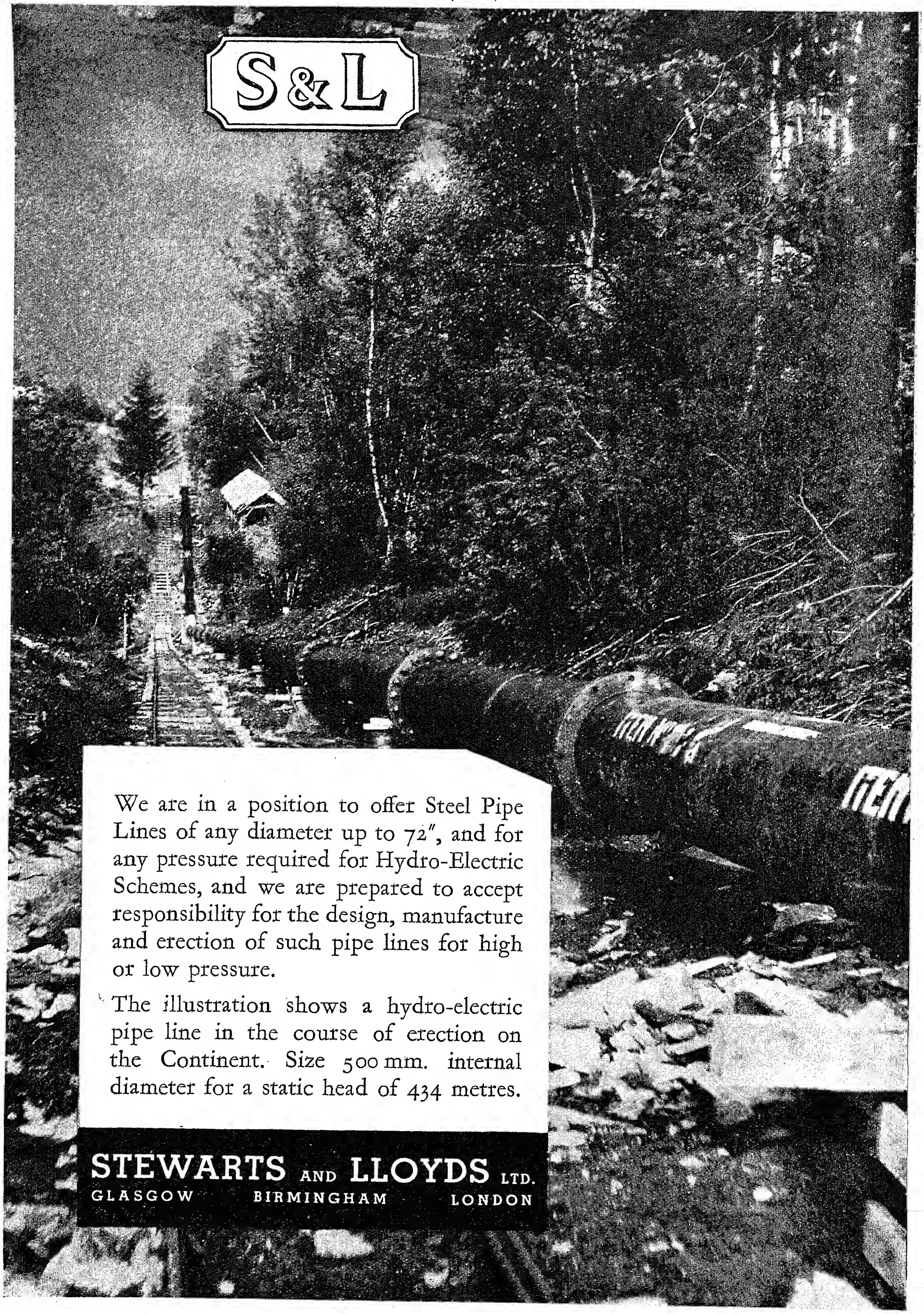
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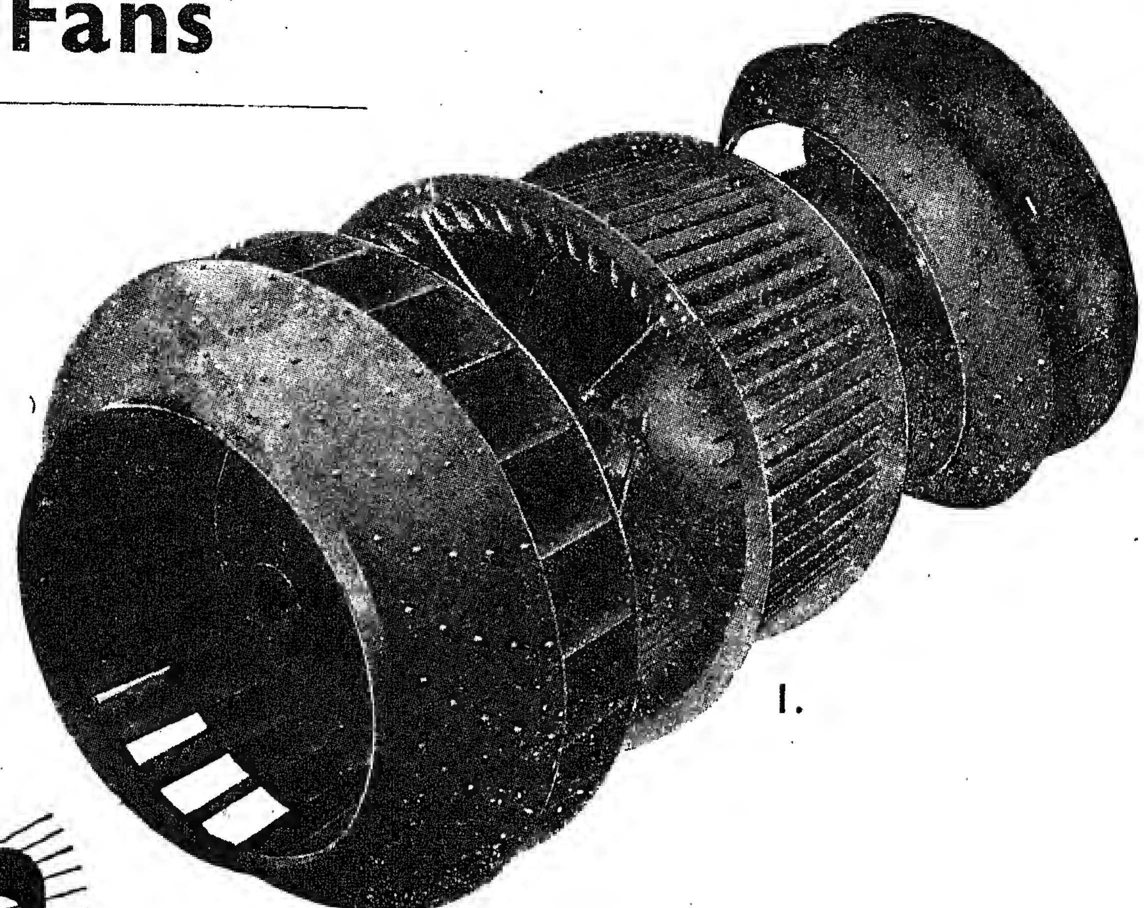

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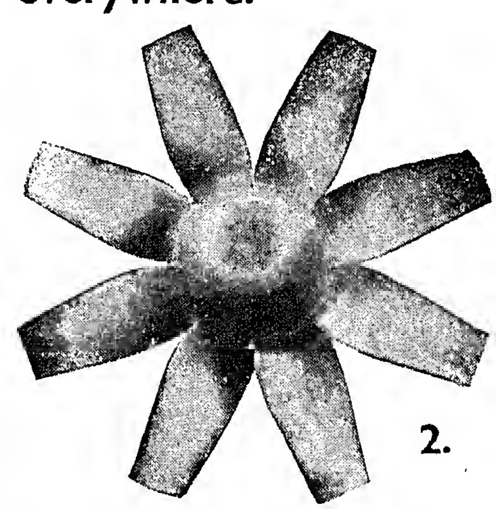
PROPELLER

★ Write for new Catalogue Ref. No. SF167, summarising the range of Forward, Radial and Backward Bladed "Sirocco" Centrifugal Fans which . . .



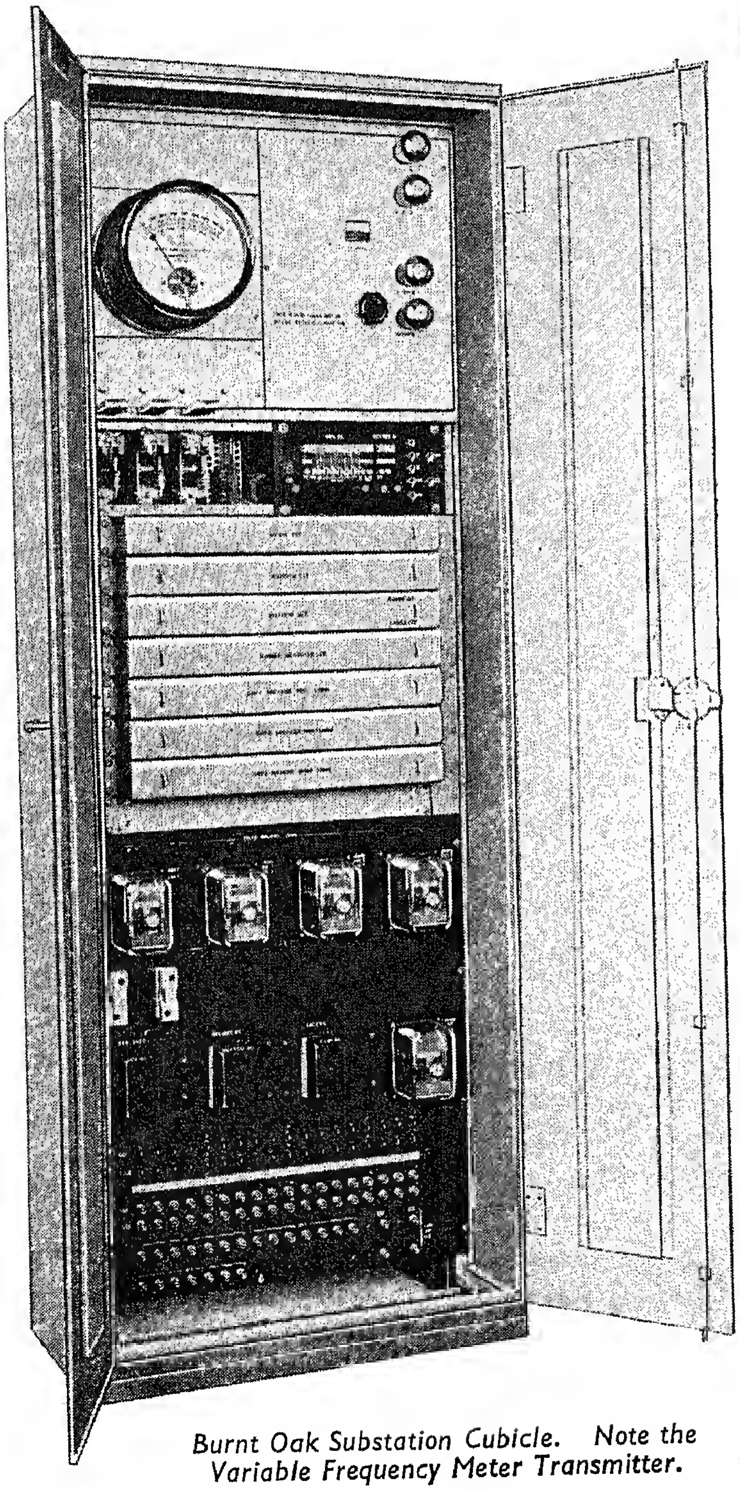
2.

Satisfy the Stringent requirements of

MODERN TIMES

★ ADVERTISEMENT OF DAVIDSON & CO. LTD., SIROCCO ENGINEERING WORKS, BELFAST

Remote Control for Electric Traction



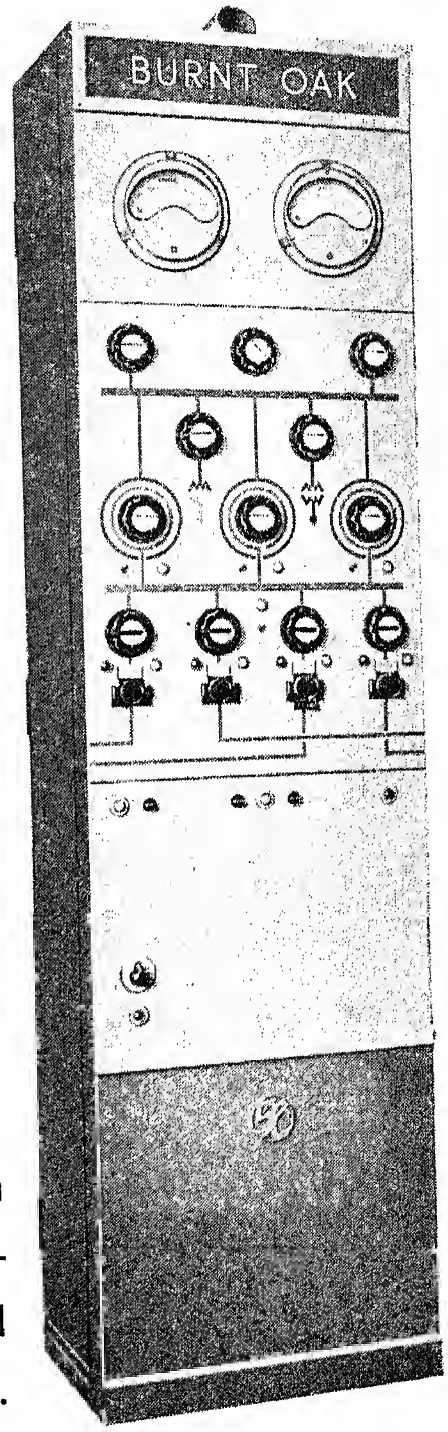
Burnt Oak Substation Cubicle. Note the Variable Frequency Meter Transmitter.

ONE of the first Remote Control installations on the L.P.T.B. system, employing 2 pilot wires only to provide control and metering of the H.T. switchgear and 3 rotary converters at Burnt Oak Substation.

The service is protected against pilot line failure by arranging to transfer, with a single operation, the control equipment to spare lines in a separate cable on the other side of the track.

Standard Telephones & Cables Ltd., in collaboration with British Thomson-Houston Co. Ltd., designed and installed the equipment.

Full details gladly supplied upon request.



Control Panel using a new Combined Type of Control Key and Indicator.

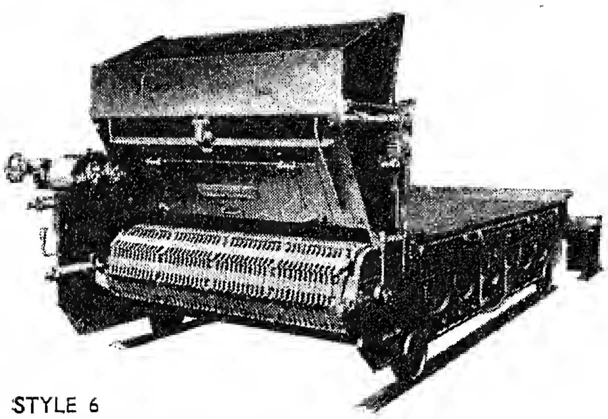
Standard Telephones and Cables Limited

NEW SOUTHGATE **LONDON, N.11**

Telephone : ENTERPRISE 1234

STOKERS

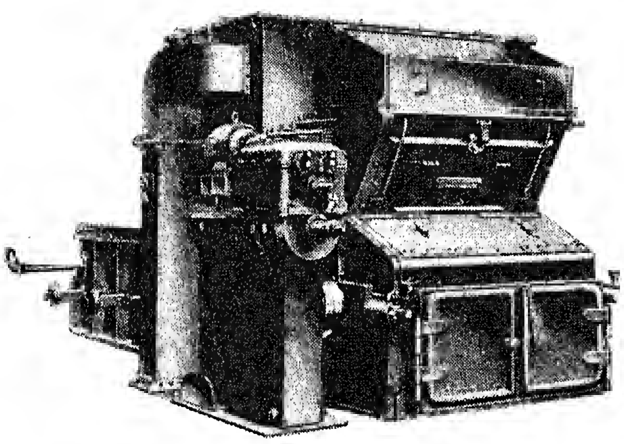
THE Babcock & Wilcox Stoker is the outcome of the Company's experience in the design and manufacture of stokers from 1883 to the present day, and the features of the present stokers were developed with the sole idea of producing a sound product based on the results obtained in many thousands of installations dealing with all classes of fuel.



STYLE 6

The Company manufactures three types of stokers, viz. the Styles 6 and 31 Chain Grate Stokers and the Style 28 Travelling Grate Stoker. All types are suitable for burning any free-burning bituminous coal, and the Styles 31 and 28 Stokers are, in addition, particularly applicable for anthracite, coke breeze, lignite, low volatile fuels, and low grade fuels generally.

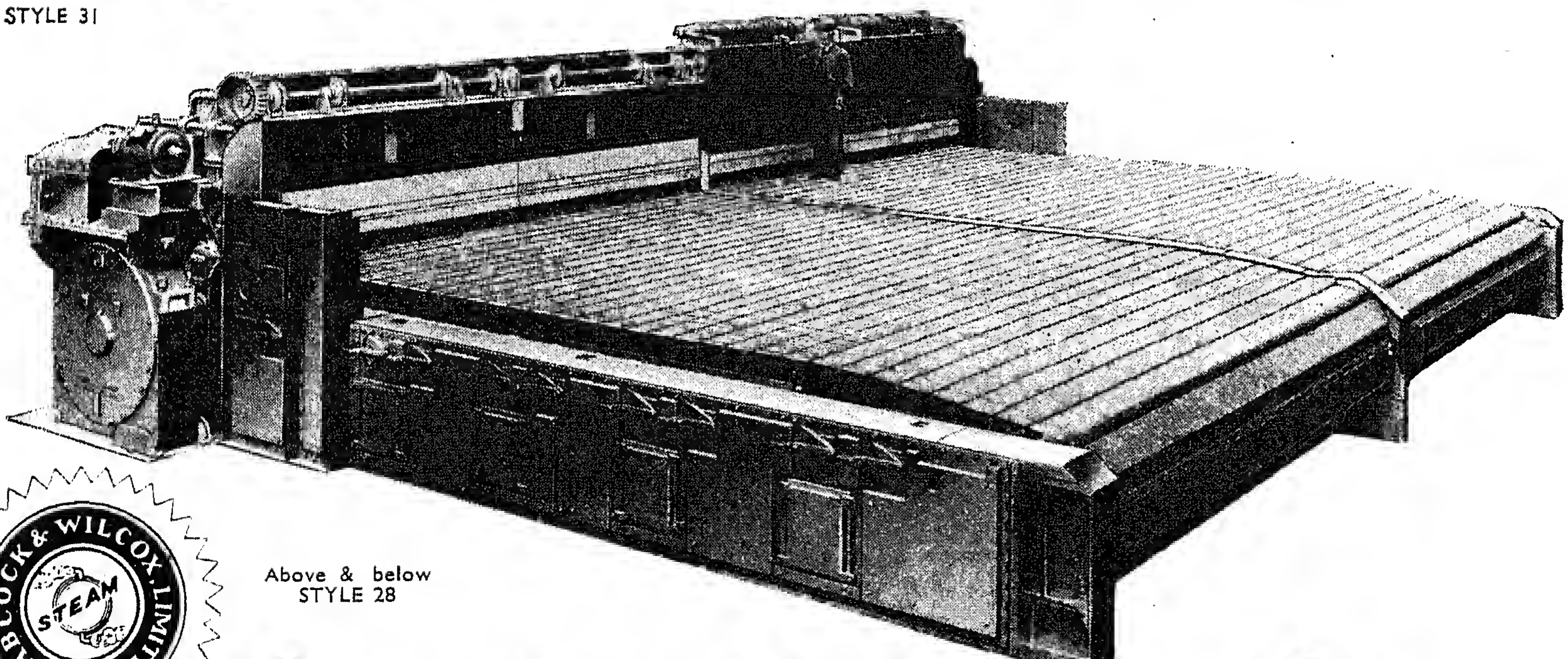
The use of each style of stoker is governed by the type of fuel to be burned, the load to be carried and the range of load to be covered, which factors are too broad to enable a single design of stoker to be applied universally.



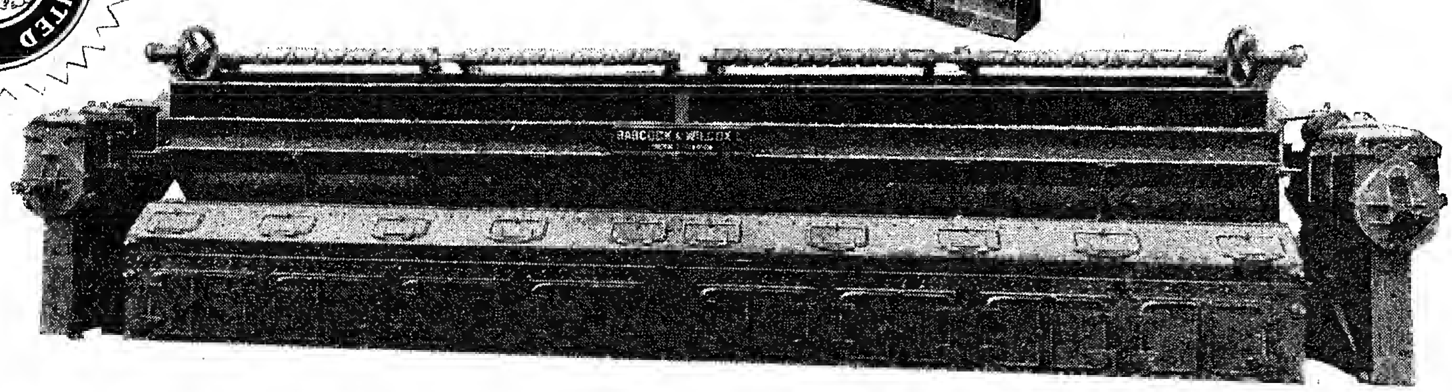
STYLE 31

The bottom illustrations show a Style 28 Stoker 33′ 0″ wide, which is one of 22 such Stokers supplied to a single Power Station. All the illustrations are taken from our recent publication, a copy of which will be sent on request.

CATALOGUE No. 1208—STOKERS



Above & below STYLE 28



BABCOCK & WILCOX LTD.

BABCOCK HOUSE, 34 FARRINGDON STREET, LONDON, E.C.4.

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